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POLLEN ANALYSIS AND RADIOCARBON DATING
OF LATEGLACIAL AND EARLY FLANDRIAN
DEPOSITS IN SOUTHERN PERTHSHIRE

J.J. LOWE

Thesis presented for the degree
of Doctor of Philosophy

University of Edinburgh

1977

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In addition, parts of this thesis are included in papers by Gray J.M. and Lowe, and Lowe and Walker, M.J.C. in the forthcoming volume <u>Studies in the Scottish Lateglacial Environment</u>, edited by Gray J.M. and Lowe J.J., and to be published by Pergamon Press (Oxford) in March, 1977.

Summary

This thesis describes the results of pollen analysis and radiocarbon dating of mainly basal sediments from enclosed presently peat-filled hollows in southern Perthshire, and the environmental implications of the results are discussed with special emphasis on the glacial sequence and the development of vegetation and soils during the Lateglacial and early Flandrian in southern Perthshire. The pollen diagrams presented are all based on relative pollen percentages, and in interpreting such diagrams two approaches are considered to be fundamental. Firstly, a number of major problems that affect the interpretation of pollen assemblages in general but Lateglacial assemblages in particular are discussed in detail prior to the correlation and interpretation of the local pollen zones. Secondly, since for a variety of reasons the regional importance of particular taxa may be strongly misrepresented in any individual pollen diagram, interpretations of the local pollen zones are to a large extent influenced by the results of similar investigations for other parts of the country. Thus reviews of and comparisons with data from other parts of Scotland (and selectively from the British Isles as a whole) form an important part of this thesis. In addition, useful indications of palaeoenvironmental changes have resulted from the analysis of deteriorated pollen grains. This aspect of pollen analysis is usually ignored in routine pollen counting. The causes of the different kinds of deterioration as well as interpretations of their varying frequency are discussed in some detail.

Evidence from the Lateglacial deposits in southern Perthshire suggests that plant colonisation commenced shortly after 13,000 B.P. and that deglaciation was widespread by that time. Plant successions followed an uninterrupted sequence between about 13,000 and 11,000 B.P. (the Lateglacial Interstadial) from the predominantly open-habitat taxa of the colonisation period, to the closed grasslands with juniper, willow

and copses of tree birch that characterised the lower-lying areas towards the end of the Interstadial. Moss heaths and poor grassland communities characterised the higher slopes. After 11,000 B.P. climatic conditions became much harsher, resulting in the Loch Lomond Readvance of glaciers, the break-up of existing soils, and revertence to open-habitat plant communities throughout southern Perthshire during the Loch Lomond Stadial (11,000 - 10,000 B.P.). A number of valley glaciers existed in southern Perthshire at this time, with the lowest and most southerly glacier terminus in this region near Callander. Rapid climatic amelioration shortly before 10,000 B.P. resulted in the cessation of solifluction processes, and a plant succession was then initiated that led to the immigration of birch woodland into parts of this area by about 9,500 B.P.

During the Flandrian a basically similar vegetational history is recorded at each site, with the following main phases: the expansion of juniper, the immigration and expansion of birch woodland, the development of a dominant birch-hazel woodland, and the decline of hazel following the immigration of elm and oak. At three sites the main Alnus rise is recognised, and the Elm Decline is positively identified at only one site. The climax forest of lowland Perthshire was a mixed oak-elm-birch association probably associated with brown forest soils. On upland sites woodlands were much lighter with birch the most important tree, the climax forest varying between birch-alder-hazel and birch-alder-pine, with oak invading some of the higher valleys. At about 6,500 B.P. marked changes in mire stratigraphy, pollen assemblages and amounts and type of deteriorated pollen are recorded, probably related to a major transition from a relatively dry climate to a climate with markedly oceanic characteristics.

The Lateglacial and early Flandrian radiocarbon dates from sites in southern Perthshire are compared with other available dates from Scotland and the chronology and terminology of the Lateglacial are

discussed. It is concluded that chronostratigraphic boundaries are at present poorly defined and that boundaries proposed in recent schemes may bear little relationship to times of major climatic change in Scotland. The thesis concludes by stressing the need for more detailed analyses for sites in southern Perthshire, employing absolute pollen counts, the analysis of deteriorated pollen and spores, and analysis of coleopteran remains in Lateglacial and early Flandrian sediments.

Acknowledgements

I owe a special debt of gratitude to my two supervisors, Dr. Brian Sissons and Dr. Walter Newey. Their interest in all aspects of this thesis was untiring, and I will always value the advice and encouragement they gave in the field and in the laboratory. Financial help from the University of Edinburgh is very gratefully acknowledged, not only for the award for three years of a postgraduate studentship, but also for a number of grants that enabled me to travel to institutions, conferences and field meetings in the British Isles, Austria, Germany and Switzerland. Radiocarbon dates for my work were assayed free of charge by the Niedersächsisches Landesamt für Bodenforschung, Hanover, and I wish to express my gratitude to Dr. Mebus Geyh, the director of that institution, for securing these facilities and for the interest he has shown in my project. Thanks are also due to the City of London Polytechnic for financing a large amount of photo-copying and photographic work.

I am indebted to a large number of colleagues for their help with fieldwork. Though space does not allow me to name them all I must mention Miss Elspeth Insch, Mr. Graham Gow, Dr. Murray Gray, Mr. Donald Sutherland, Dr. Ken Thompson, Dr. Jimmy Young, and especially Dr. Mike Walker. I am grateful to Professor Yrjö Vasari of the University of Oulu, Finland, who interrupted his own very busy field programme in 1971 to allow the use of his own equipment and, together with his son, Peter, helped collect cores at Tynaspirit. Mike Walker and Ken Thompson kindly permitted access to unpublished data, and I must also thank all those who have given their permission to quote unpublished records and ideas. I thank Dr. S.E. Durno of the Macauley Institute for Soil Research, Aberdeen, and Mr. Eric Caulton of Moray House College of Education, Edinburgh, for help in the identification of some problematic pollen grains and spores.

I sincerely thank Mrs. Margaret Jones, Miss Mavis Teed and Mr. Derek Almond for cartographic work, and Mr. Alan Gillard for reproduction of figures (all of the City of London Polytechnic). Thanks are also due to Miss Pat Aylott of King's College, University of London, for reproduction of some of the figures. Figures 17, 18, 22, 33 and 34 are reproduced by kind permission of Pergamon Press (Oxford) Ltd.

Lastly, but by no means least, I thank my wife, Jeanette, for her constant help and encouragement and continued unselfishness since the 19th September 1969.

J. John Lowe

Contents

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Note: Folded figures do not have page numbers and, with the exception of Fig. 23, are to be found either at the end of chapter 6 (all figures for deteriorated pollen) or at the back of the volume (all pollen diagrams for which pollen assemblage zones have been defined).

F/B = located at back of volume
F/6 = located at end of chapter 6

List of Tables

INTRODUCTION

In this thesis pollen profiles and radiocarbon dates are presented for several sites situated in southern Perthshire. The study concentrates on Lateglacial and early Flandrian deposits, and the area was chosen for several main reasons. Firstly, at the time of starting this work (1970) few Lateglacial pollen profiles had been published for sites within the Grampian Highlands or situated close to the Highland edge, and radiocarbon dates from Lateglacial and early Flandrian sediments from Scotland were rare. Secondly, the only Lateglacial pollen profile published for the whole of Perthshire at that time, Loch Mahaick (Donner, 1958), presented results for organic sediments only, for the Lateglacial minerogenic sediments were found to contain few pollen grains. Thirdly, the sites discussed here are critically located with regard to Lateglacial ice limits recently proposed for parts of southern Perthshire on the basis of extremely detailed morphological mapping (Thompson, 1972). Fourthly, the sites lie within an important transition zone in terms of present-day potential climax forest communities (McVean and Ratcliffe, 1962) and in terms of suggested climax forest communities for the middle Flandrian (Godwin, 1975).

The main aim of the thesis is to test the validity of current hypotheses concerning vegetational and glacial history in Scotland in general and in southern Perthshire in particular. To this end it is intended to present a detailed picture of vegetational history in southern Perthshire and to discuss its palaeoenvironmental implications, and also to assess the usefulness of pollen-stratigraphy and radiocarbon dates in the establishment of a chronology of Lateglacial and early Flandrian events in Scotland.

The sites discussed are located close to the Highland Boundary Fault, in the vicinities of Callander, Crieff and Amulree (Fig. 1). In the area considered (Fig. 2) the Highland Boundary Fault forms a marked geological

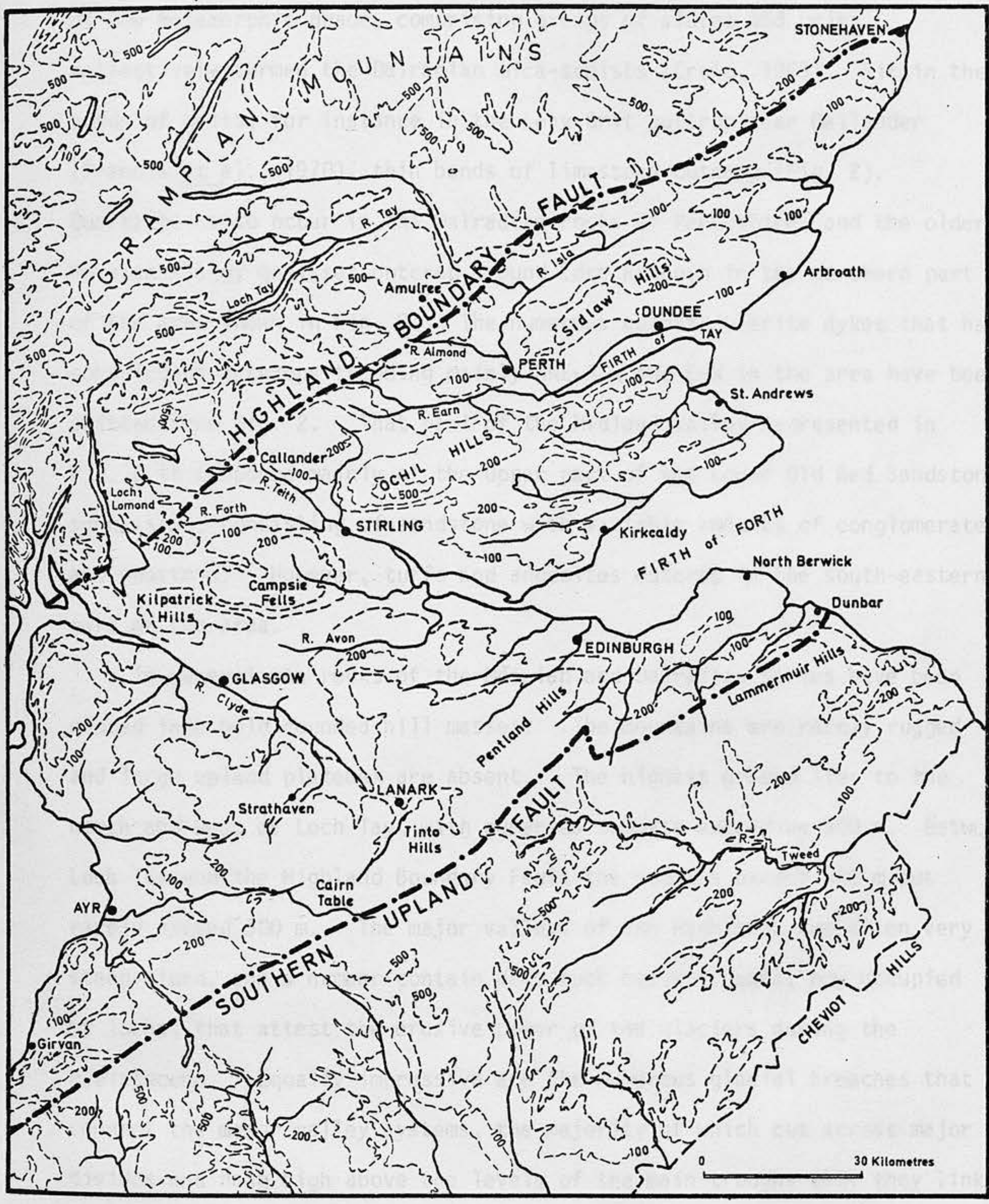

FIGURE 1 General location of Callander, Amulree and other parts of the study area. Contours in metres.

boundary between the Dalradian rocks of the southern edge of the Grampians and the comparatively less resistant Lower Old Red Sandstone sediments of the Midland Valley. The Dalradian rocks consist entirely of metasediments of low metamorphic grade, comprising groups of slates and grits collectively termed the Dalradian mica-schists (Craig, 1965). Within the bands of grits, for instance in the Leny Grit outcrop near Callander (Francis et al., 1970), thin bands of limestone outcrop (Fig. 2). Quartzites also occur in the Dalradian rocks of Perthshire, and the older Moinian flaggy gneisses outcrop around Loch Rannoch in the northern part of the area shown in Fig. 2. The numerous quartz-dolerite dykes that have conspicuous outcrops trending mainly NNE-SSW and E-W in the area have been omitted from Fig. 2. That part of the Midland Valley represented in Fig. 2 is composed mainly of the upper part of the Lower Old Red Sandstone succession, consisting of sandstone with variable amounts of conglomerate and mudstone. However, tuffs and andesites outcrop in the south-eastern part of the area.

In general the rocks of the Moinian and Dalradian series have been eroded into bold rounded hill masses. The mountains are rarely rugged and large upland plateaux are absent. The highest ground lies to the north and west of Loch Tay, with numerous summits exceeding 900 m. Between Loch Tay and the Highland Boundary Fault the summits exceed 600 m but rarely exceed 900 m. The major valleys of the Highlands are often very steep-sided, and a number contain deep rock basin troughs, now occupied by lochs, that attest the erosive power of the glaciers during the Pleistocene. Equally impressive are the numerous glacial breaches that connect the major valley systems, the majority of which cut across major divides and hang high above the levels of the main troughs that they link. Examples of the latter are Glen Ogle, between the valleys of Loch Earn and the River Dochart, and the watershed breach that occurs to the south of Amulree, stretching between Strathbraan and Glenalmond.

The lower-lying areas of the Midland Valley to the south and east of

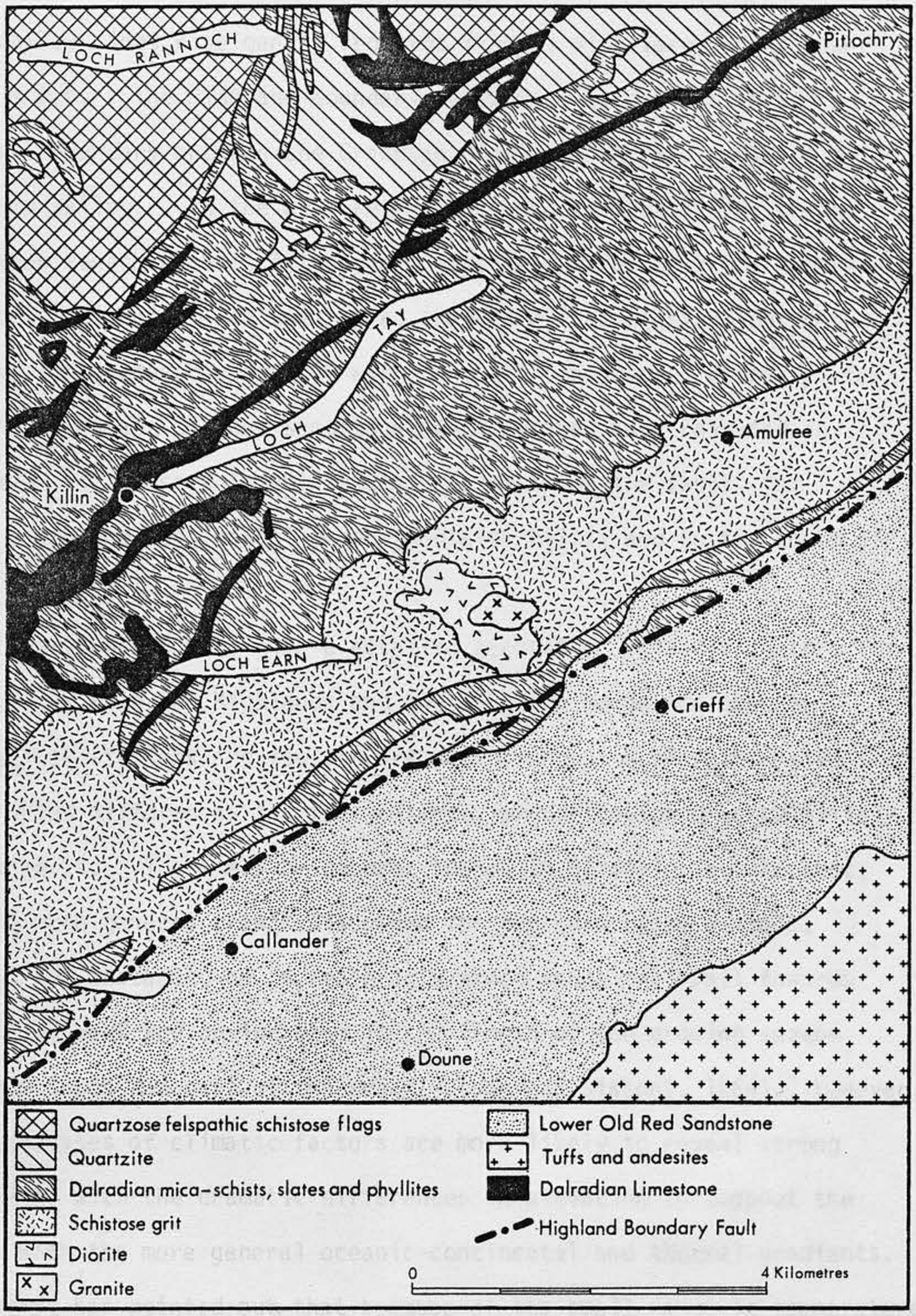

FIGURE 2 Major rock types in central and southern Perthshire.

Crieff and between Callander and Doune reflect the less resistant sedimentary rocks of the Lower Old Red Sandstone succession. The broad valleys of the Teith, the upper Forth and the upper Earn have floors below 30 m O.D., and the valley sides rise gently from the floors, with large areas lower than 100 m O.D. The Highland Boundary Fault usually delimits a basic topographic boundary between the Grampian Highlands and the lowlands of the Midland Valley. In the area represented in Fig. 2 this fault runs through Loch Venacher, Glen Artney, and north-eastwards past the southern exit of the Sma' Glen. In this area, therefore, the Highland Boundary Fault does not correspond exactly with a marked topographic boundary, for relatively resistant Old Red Sandstone conglomerates have resulted in considerable hill masses immediately to the south of the fault, for instance south and west of Callander (Menteith Hills) and to the south of Comrie.

It is not possible to give a detailed account of climatic factors for the area. As with the Highlands and the Highland Border in general meteorological stations are few and frequent changes in elevation give rise to marked differences in, for instance, precipitation over relatively short distances. There may be general trends in climatic factors that, in keeping with general trends discerned for the country as a whole, result in, for instance, an increase in average annual rainfall towards the north and west and an increase in the length of the growing season towards the south and east of the area (Watson and Sissons, 1964). However, detailed analyses of climatic factors are more likely to reveal strong relationships with the dramatic differences in elevation throughout the area than with the more general oceanic-continental and thermal gradients. Manley (1952) has pointed out that because of the small range in temperature that is typical of Scotland the effect of the lapse rate is an important factor which has serious consequences with regard to the growing season. The drop in temperature at 1000 m due purely to altitude can be about 6C^{o}. There is probably an intricate pattern of variation of bio-climatic factors

(Miller, 1973) throughout southern Perthshire, which in the past may have resulted in sudden and frequent changes in soil and vegetation.

With the exceptions of upland blanket peats, lowland basin mires, and the improved agricultural land of parts of the main Highland valleys and the lowlands to the south of the Highland Boundary Fault, most of the area today is moorland, either grass, heather, or mixed grass-sedge moorland. Plantations of coniferous trees were first introduced into southern Perthshire on a large scale in the early eighteenth century, comprising mainly larch trees, and with the setting up of the Forestry Commission in 1919 planting increased. This involved mainly pine, spruce and larch, but also the introduction of more exotic species such as Douglas fir. The largest forests in southern Perthshire occur in Strathyre, the Trossachs and around Comrie. However, these forests are still limited to main valleys and the Highland Border, and most of the Highland areas of Perthshire remain under moorland. Small stands of mixed deciduous forest occur on calcareous substrates in central Perthshire, but these are rare.

The almost complete destruction of the original forest cover of Scotland commenced in Neolithic times and has continued until the present day. However, McVean and Ratcliffe (1962) have attempted a reconstruction of the natural distribution of certain forest species in Scotland. Their map of Scottish woodlands, part of which is represented in Fig. 3, is based on available evidence from the present distribution of the main woodland types and tree species, known ecological requirements of the species, pollen analysis, sub-fossil remains in peat and recorded history. Their hypothesis indicates that under present climatic conditions but prior to the onset of large-scale human forest clearance, the forest cover of southern Perthshire would have been transitional between the predominant oak forest with birch of the Midland Valley and the predominant pine forest with birch and oak of the Highlands. According to Godwin's (1975) reconstructed forest composition for Britain during the middle Flandrian,

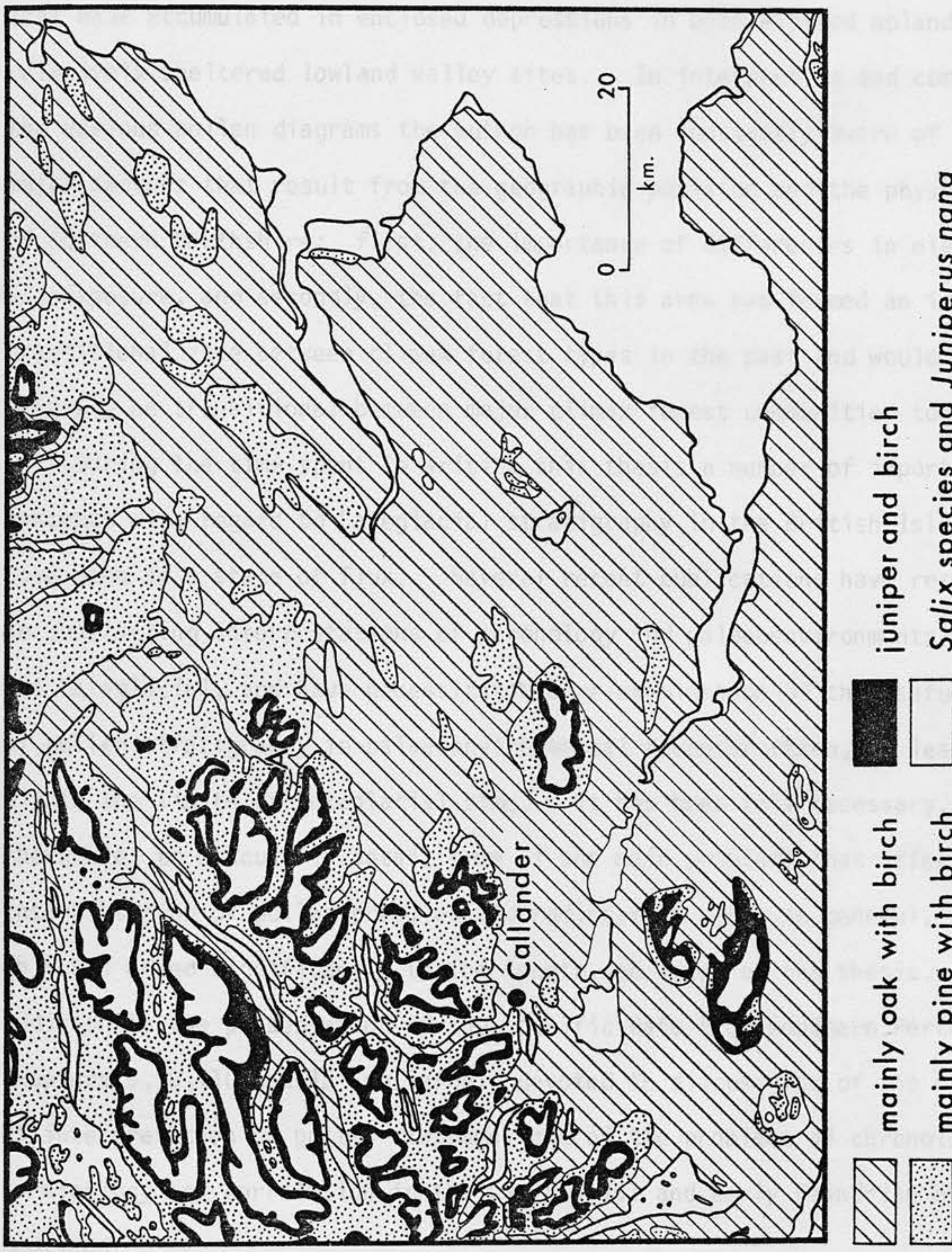

FIGURE 3 Reconstructed distribution of oak, pine and birchwood and of shrubs of Salix and Juniperus in east-central Scotland during the present climatic period (after D. N. McVean and D. A. Ratcliffe, 1962). A = location of Amulree.

the Highland Border was probably also an important zone of transition between the alder-oak-elm forests of the Midland Valley and southern Scotland, and the pine-birch-alder forests of the Highlands.

The pollen profiles presented in this thesis relate to sediments that have accumulated in enclosed depressions in both exposed upland and relatively sheltered lowland valley sites. In interpreting and comparing the various pollen diagrams the author has been constantly aware of two major factors that result from the geographic position and the physiography of southern Perthshire: first, the importance of differences in elevation and exposure, and secondly, the fact that this area has formed an important transitional zone between climax forest types in the past and would probably be transitional between major climax forest communities today.

During the time spent in writing this thesis a number of important concepts with regard to Lateglacial stratigraphy in the British Isles have been in a state of flux. Several recent publications have resulted in conflicting interpretations of chronology and palaeoenvironments during the Lateglacial, and have necessitated a re-examination of the usefulness of pollen-stratigraphy in palaeoenvironmental reconstruction, at least within the limits of Lateglacial time. It has been felt necessary, therefore, to discuss in detail some of the main problems that affect the interpretation of pollen profiles and radiocarbon dates in general, and this has added significantly to the length and scope of the thesis. In addition to the presentation of the specific data from southern Perthshire, chapters 5, 9, 10 and 12 are largely devoted to discussions of the problems of interpretation of pollen diagrams, and of the problems of chronology, terminology and correlation in the Lateglacial and early Flandrian of Scotland.

Throughout the thesis the following terms are used with precise chronostratigraphic definitions. The 'Lateglacial' refers to the time between 13,000 and 10,000 B.P. This is divided into the 'Lateglacial Interstadial' (13,000 - 11,000 B.P.) and the 'Loch Lomond Stadial' (11,000 -

10,000 B.P.). The term 'postglacial' is used rarely and only with an imprecise meaning in view of the evidence of radiocarbon dates presented in this thesis that conflict with other previously-published dates for deglaciation following the Loch Lomond Readvance. These terms, the complicated Lateglacial/Flandrian transition, and Lateglacial subdivision and nomenclature in general are discussed in more detail in chapter 10. Chapter 1 presents a brief review of some of the recent research into Lateglacial and Flandrian environmental changes in Scotland, which provides an important foundation for many of the arguments developed in subsequent chapters.

CHAPTER 1

Reconstructing the historical development of the Late Devensian and Flandrian environments of the British Isles

1. THE LATE DEVENSIAN ICE-SHEET

According to the recent special report of the Quaternary Geological Society (Mitchell et al., 1973), the Late Devensian period is the last of three major subdivisions of the Devensian cold stage (equivalent to the Weichselian of the continental stratigraphy). It follows the long Middle Devensian interstadial period (50,000 to 26,000 B.P.), and it ends at 10,000 B.P., which is the date recommended by the Holocene Commission of INQUA (1969) for the beginning of the Holocene (Flandrian) time. The Late Devensian is thus defined in chronostratigraphic terms in an attempt to avoid those difficulties experienced in the past with definitions based on lithostratigraphic and biostratigraphic criteria (Mangerud, 1970; Shotton, 1973; Vita-Finzi, 1973).

There is now much evidence to suggest that large parts of the British Isles were ice-free for long periods during the Middle Devensian. A number of radiocarbon dates are available from interstadial deposits from the Midlands of England, upon which the definitions for the boundaries of the Middle Devensian are based (Coope and Sands, 1966; Morgan, 1973; Shotton, 1973; Coope, 1975). Three dates are available that indicate the absence of ice in Scotland in Middle Devensian times. A buried podsol near Teindland in Morayshire yielded a date of 28,140 +480 -450 B.P. (FitzPatrick, 1965). A bone of woolly rhinoceros found in sand and gravel deposits at Bishopbriggs near Glasgow was dated to 27,550 +1370 -1680 B.P. (Rolfe, 1966). Finally, a date of 27,333 ± 240 B.P. was obtained from peat overlain by till on the Isle of Lewis (von Weymarn and Edwards, 1973).

The Middle Devensian interstadial is regarded as a period of mainly polar desert conditions with occasional climatic ameliorations, such as that indicated by the relatively more temperate fauna at Upton Warren (Mitchell et al., 1973). The build-up and decay of the Late Devensian ice-sheet that followed this cold desert period has left a highly complex stratigraphical sequence of glacial and fluvioglacial deposits, particularly in the Midlands and Northern England. A schematic sequence of Upper Sands, Upper Boulder Clay, Middle Sands, and Lower Boulder Clay has been applied to complex successions in several districts, but Evans and Arthurton (1973) point out that this scheme has been over-simplified and inconsistently interpreted in the past. Radiocarbon dates from 'Middle Sands' in Westmorland (Shotton et al., 1970) and the Cheshire-Shropshire Basin (Boulton and Worsley, 1965) show that parts of this complex are of Middle Devensian age or older, whereas in other localities the entire sequence of deposits appears to have been produced by the stagnating Late Devensian ice-sheet (Hill and Prior, 1968; Penny et al., 1969; Evans and Arthurton, 1973). There are few radiocarbon dates presently available to help solve problems of succession and correlation in many parts of the British Isles. Nevertheless, it is currently believed that at the height of the Late Devensian glaciation, between about 17,000 and 20,000 years ago, the ice extended at least as far south as Holderness in Yorkshire (Penny et al., 1969; Shotton and Williams, 1971).

The pattern of deglaciation following the maximum of the Late Devensian ice-sheet is also an area of much debate, particularly in attempting to establish the number of readvances of ice that may have taken place. From available morphological and stratigraphical evidence in Scotland Sissons (1967a) proposed three major readvances of Devensian ice. These he termed the Aberdeen-Lammermuir Readvance, the Perth Readvance, and the Loch Lomond Readvance in order of both decreasing age and decreasing areal extent. However, in a recent reappraisal of the evidence, Sissons (1974a) suggests some considerable modifications to his original concept.

The Aberdeen-Lammermuir Readvance is now completely rejected because of the absence of any positive features indicative of a readvance. The evidence for a Perth Readvance is more confusing. Originally the concept of a readvance of ice was based on a section exposed in the valley of the River Almond in Perthshire which revealed a basal till overlain by varved sediments, which were in turn buried under what was interpreted as outwash sands and gravels (Simpson, 1933). However, the sand and gravel deposits, and most of the features quoted by Sissons (1967a) in support of a Perth Readvance, are merely indicative of widespread ice decay, of melting and stagnating ice, and not of actively advancing ice.

Further, on the basis of available radiocarbon dates, it was proposed that the Perth Readvance culminated between about 13,500 B.P. and 13,000 B.P. In the Kilmaurs district of Ayrshire a mammoth tusk from stratified deposits that underlie till was dated to 13,700 +1300 -1700 B.P. (Sissons, 1967b), whilst the earliest available dates from remains that post-date the supposed Perth Readvance sediments were 12,940 ± 250 B.P. (Lockerbie, in Dumfriesshire; Bishop, 1963) and 12,814 ± 155 B.P. (Loch Droma in Ross-shire; Kirk and Godwin, 1963).

It would now appear that the mammoth tusk date from Kilmaurs is very much in doubt, for a reindeer antler from the same Kilmaurs site has recently assayed at greater than 40,000 B.P. (Shotton et al., 1970). In addition, Paterson (1974) has reinterpreted the morphological evidence in much of Perthshire and suggests that the features originally taken to indicate the Perth Readvance instead result from a gradual retreat of the main Late Devensian ice-sheet, with possibly some occasional stillstands. In only one location, in the vicinity of Perth (Moneydie section in the Shochie Valley), is there evidence of a till deposit thought to represent a readvance of Late Devensian ice, and this may well be of no significance regionally.

There is positive evidence for only one distinct readvance of ice in the Late Devensian, the so-called Loch Lomond Readvance. The evidence for this glacial oscillation is presented in more detail in the following section. The Loch Lomond Readvance (equated with the Younger Dryas period of continental stratigraphy) is regarded as the last phase of glacial activity to have affected Britain, a phase when glaciers were mostly limited to upland regions (Sissons, 1976a). The pattern of glacial activity throughout the earlier parts of Late Devensian time remains unknown, and, until some positive evidence is forthcoming, glacial and fluvioglacial deposits older than the Loch Lomond Readvance cannot be placed with certainty within the Late Devensian time-span.

2. EVIDENCE FOR A LATE DEVENSIAN READVANCE OF ICE: THE LOCH LOMOND READVANCE

The relative age of the Loch Lomond Readvance was first established by Donner (1957) on the basis of pollen studies of the sediments of lake basins critically located with regard to the presumed limits of the Loch Lomond Readvance. The work of the present thesis is essentially based on this approach. Donner's analyses rested on the recognition of eight main zones of vegetational development, as indicated by pollen spectra, reflecting climatic developments in the British Isles throughout the Lateglacial and Flandrian periods. A fuller account of the pollen zonation scheme and relevant radiocarbon dates appears in Godwin 1956 and 1975, and in Godwin, Walker and Willis 1957.

The first three of the vegetational (pollen) zones refer to the end of the Late Devensian period, the Lateglacial, and they were interpreted as indicating a relatively warm interstadial period correlated with the Alleröd of Denmark (Zone II), a cold period which preceded the Alleröd (Zone I - the Older Dryas of continental stratigraphy), and a post-Alleröd cold period representing the stadial conditions of the Loch Lomond Readvance (Zone III - the Younger Dryas). This oscillation in climatic development was recognised both in the nature of the pollen analyses and in the lithostratigraphic characteristics of associated deposits. The lithostratigraphic sequence of predominantly minerogenic deposits, organic-rich (peat or gyttja) deposits, and minerogenic deposits (usually fine clay in lake sites) represented the development of zones I, II and III respectively. Donner's logical assumption was that those basin sites that provided evidence of a Lateglacial oscillation in their sediments (ie presence of Zone II deposits) must lie outside the limits of the Loch Lomond Readvance, whereas basins that lie within these limits can only contain Flandrian or late Zone III deposits as their earliest accumulation.

Around the southern end of Loch Lomond and in the western part of the Forth Valley are end-moraine complexes recording the limits of large glaciers whose ice sources lay in the higher ground towards the north and west (Fig. 4). These two glaciers have been termed the Loch Lomond Glacier and the Menteith Glacier respectively (Sissons, 1967a). Proof of a re-advance of ice is provided by the shells in the morainic drift of both of these complexes (Simpson, 1933). At a site north-east of Drymen, on the presumed ice-free ridge between the Menteith and Loch Lomond glaciers, Donner found evidence for the Lateglacial oscillation in the lithostratigraphy and biostratigraphy of the sediments, but in those sites that he studied that lay inside the readvance limits only postglacial (Flandrian) sediments were recorded. Donner thus concluded that the Loch Lomond and Menteith glacier limits are of Zone III age. Further analyses of this nature published by Donner concern the Oban district, where this analytical procedure was applied to the theoretical 'Moraine Glaciation' of Charlesworth (Charlesworth, 1955; Donner, 1957). Evidence for Lateglacial stratigraphy was absent from sites within the limit of the 'Moraine Glaciation', but a Lateglacial stratigraphic sequence was advanced for deposits at two locations outside this limit.

Such evidence as presented by Donner does not alone prove the readvance nature of the morphological forms, but the positive evidence of a Late-glacial oscillation in a particular site must limit the area affected by Loch Lomond Readvance glaciers. As stated above, it is the shells incorporated in the moraines that provide evidence of ice readvance.

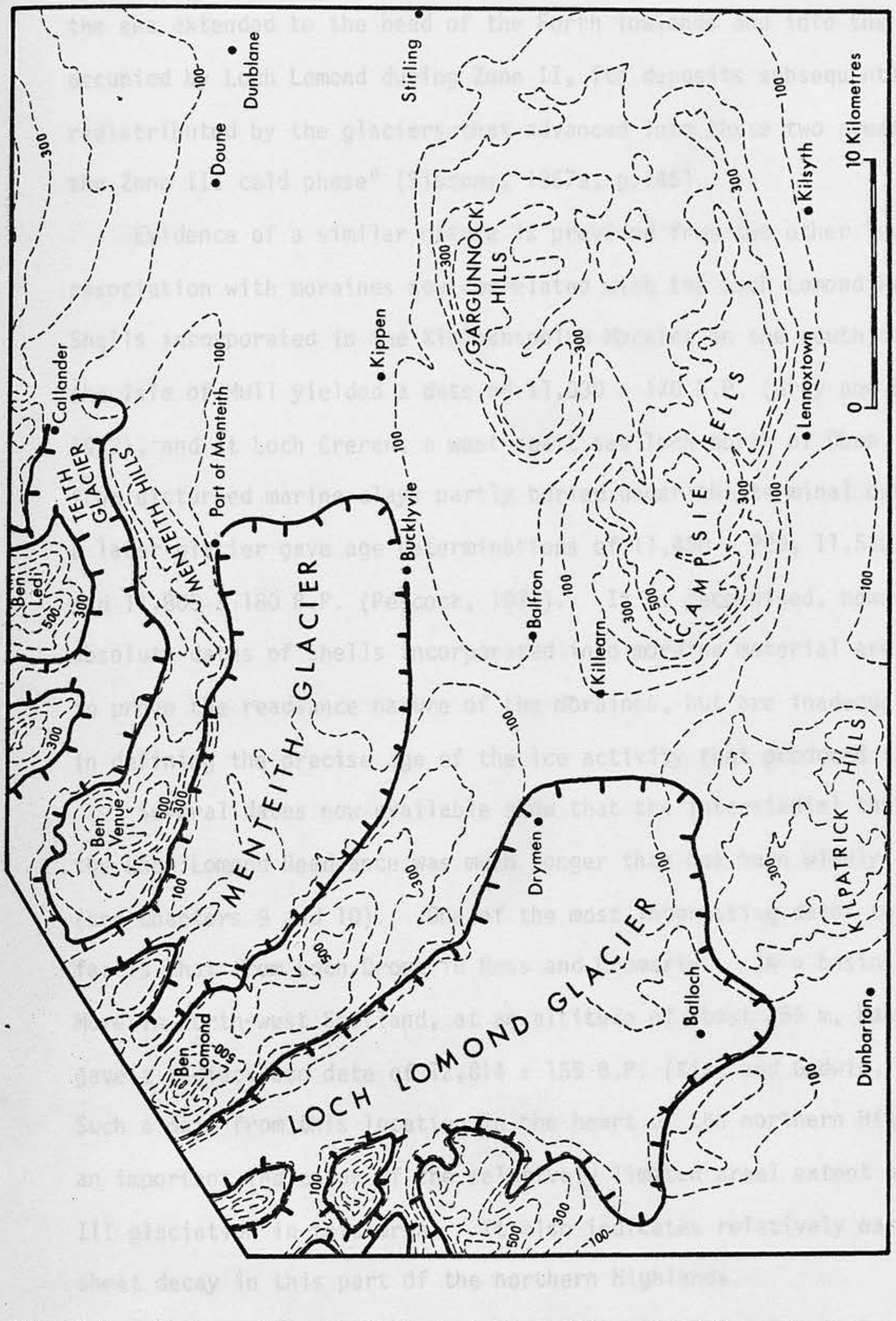

FIGURE 4 Limits of the Loch Lomond, Menteith and Teith readvance glaciers (after J.B. Sissons, 1967, and K.S.R. Thompson, 1972). Contours in metres.

Radiocarbon dating of shells found in the Menteith Moraine and in the Loch Lomond end-moraine complex gave age determinations of 11,800 ± 170 B.P. and 11,700 ± 170 B.P. respectively (Sissons, 1967b), and they imply "... that the sea extended to the head of the Forth lowlands and into the ground now occupied by Loch Lomond during Zone II, its deposits subsequently being redistributed by the glaciers that advanced into these two areas during the Zone III cold phase" (Sissons, 1967a, p.146).

Evidence of a similar nature is provided from two other locations, in association with moraines now correlated with the Loch Lomond Readvance. Shells incorporated in the Kinlochspelve Moraine on the south coast of the Isle of Mull yielded a date of 11,330 ± 170 B.P. (Gray and Brooks, 1972), and at Loch Creran, a west coast sea loch north of Oban, shells from disturbed marine clays partly buried under the terminal outwash of a later glacier gave age determinations of 11,430 ± 220, 11,530 ± 210, and 11,805 ± 180 B.P. (Peacock, 1971). It is recognised, however, that absolute dates of shells incorporated into moraine material are sufficient to prove the readvance nature of the moraines, but are inadequate for use in defining the precise age of the ice activity that produced them.

Several dates now available show that the interstadial that preceded the Loch Lomond Readvance was much longer than has been widely accepted (see chapters 9 and 10). One of the most interesting dates to emerge so far is that from Loch Droma in Ross and Cromarty. In a basin in Dirrie More in north-west Scotland, at an altitude of about 265 m, basal deposits gave a radiocarbon date of 12,814 ± 155 B.P. (Kirk and Godwin, 1963). Such a date from this location in the heart of the northern Highlands is an important indicator of the relatively limited areal extent of the Zone III glaciation in this area. It also indicates relatively early ice-sheet decay in this part of the northern Highlands.

Whilst the Loch Droma date, and several other dates to be discussed later, may possibly suggest the complete deglaciation of Britain in the pre-Zone III interstadial, mention should be made of a significantly different interpretation. From evidence in the Cairngorm Mountains Sugden (1970) proposed that the Zone III glaciation was only a minor fluctuation of ice which was still present throughout the whole of Lateglacial time. Recent evidence has forced Sugden to modify his views, for there is little evidence for ice surviving throughout the Lateglacial in or around the Cairngorm Mountains (Sugden and Clapperton, 1975). However, Peacock (1970) has argued that the large volume of ice attributed to the Loch Lomond Readvance in western Inverness-shire could not have accumulated in the time available and he therefore suggested that active ice existed in this area throughout Lateglacial times. This conflicts with other recent interpretations of available evidence from Scotland (Sissons, 1972, 1976a; Sissons and Grant, 1972; Thompson, 1972). Such a contrast of opinion over the fundamental problem of reconstructing the glacial sequence for the Lateglacial period is an issue upon which later discussions (chapters 9 and 10) have important bearing.

3. THE AREAL EXTENT OF THE LOCH LOMOND READVANCE

In Sissons' original delimitation of the Loch Lomond Readvance limits (1967a) use was made of a morainic topography regarded as of a fresh appearance in comparison to other (older) drift forms. These moraines, particularly common in many upland areas of Scotland (and less so in the Lake District), form extremely hummocky terrain comprising numerous mounds (often boulder-strewn) composed predominantly of angular and ill-sorted debris. The hummocky topography is a distinctive feature in many mountain valleys throughout the Highlands, sometimes with a clear limiting edge to the features and sometimes with an obscure one, and occasionally, as at Callander, with a clear terminal moraine providing a sharp definition to the downvalley limit of the glacier that deposited the mounds. Terminal moraines are a more frequent feature in Loch Lomond Readvance landforms in north-east Scotland (Sissons, 1967a, 1977). If this assessment of the recognition and interpretation of hummocky drift can be accepted, and if correlation with the Loch Lomond and Menteith moraines can be established, then clearly the distribution of hummocky drift would provide an indication of the degree of regional glacierization during Zone III times.

Some recent investigations have been devoted to the detailed mapping of hummocky drift and its associated features in various parts of the Scottish Highlands. On the basis of the distribution of hummocky drift in the highlands of western Perthshire Thompson (1972) was able to suggest a detailed system of glaciers in existence in that region during Zone III. From an examination of the pattern of this hummocky drift and its constituent sediments, Thompson concluded that, contrary to impressions based on the surface appearance of the deposits, the drift features are basically kames that are often thickly covered with ablation moraine, and they indicate a widespread general decay of ice associated with rapid downwasting in the eight major valley systems that he studied (Fig. 5).

Thompson delimited in detail a system of inter-connecting valley glaciers with sources of ice accumulation mostly on upland plateaux or corries, with a tendency to local ice cap development in large favoured upland basins (such as Glen Lyon), and with the largest accumulation ground for glacier ice in the area around Loch Rannoch. The proposed intricate web of sometimes totally isolated ice accumulations in Highland areas is a picture which differs greatly from earlier concepts of the 'Valley' or 'Highland Glaciation' (Movius, 1942; Charlesworth, 1955; Penny, 1964).

Further reference is made to Thompson's work in chapter 2, but brief mention will be made here of the evidence used by him to correlate the hummocky features of western Perthshire with the Loch Lomond end-moraine complex. Five main lines of argument were employed, four of them being:

(i) The Teith terminal moraine (Callander) occupies a position at the mouth of a Highland valley analogous to those of the neighbouring Menteith and Loch Lomond terminal moraines (Fig. 4).

(ii) A suite of outwash terraces formed beyond the Teith moraine passes into a buried fan that was largely deposited during a

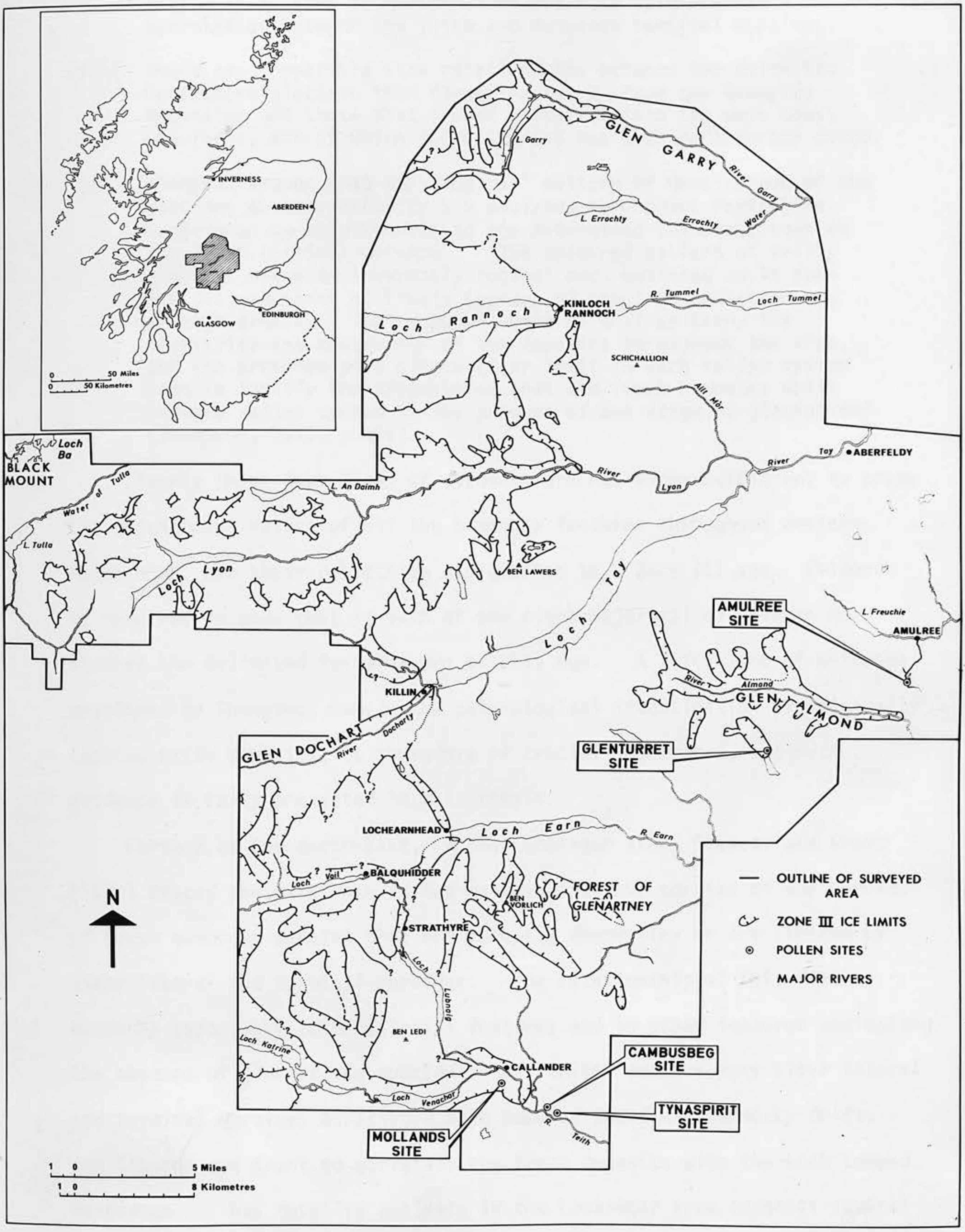

FIGURE 5 Loch Lomond Readvance ice limits in parts of Perthshire (after Thompson 1972) and location of pollen sites described in this thesis.

period of low sea-level, when the adjacent Menteith moraine was being formed. Whereas Thompson's other arguments are inferential, this factor provides positive evidence for a correlation between the Teith and Menteith terminal moraines.

(iii) There are comparable size relationships between the delimited Perthshire glaciers that flowed eastwards from the Grampian Mountains and those that flowed westwards into the west coast sea lochs, one of which (Loch Creran) has been radiocarbon dated.

(iv) Thompson argues that the "logical" pattern of development of the glaciers as determined by his analyses throughout Perthshire suggests an age relationship to age-determined features, such as the Teith terminal moraine. "The inferred pattern of valley glaciers seems an inherently logical one, matching as it does the distributions of likely sources of great accumulation and of high ground. The reasonableness of this pattern, the similarity and continuity of the deposits throughout the area, and the presence of a single clear limit in each valley system seem to justify the proposition that the fresh hummocky drift in each valley system is the product of one stage of glaciation" (Thompson, 1972, p.307).

Clearly these four lines of evidence are not alone sufficient to prove the synchronous nature of all the hummocky features throughout western Perthshire, nor their collective assignation to a Zone III age. Evidence is required to show that in each of the eight major valley systems he studied the delimited features are of this age. A fifth line of evidence mentioned by Thompson, namely the palynological investigation of critically located basin deposits, is therefore of crucial importance, and such evidence is fully presented in this thesis.

Farther to the north-east, in the Lochnagar area, Sissons and Grant (1972) traced the existence in two valleys and four corries of the spreads of fresh hummocky moraine that end abruptly downvalley or are limited by clear lateral and terminal moraines. The relationship of this fresh hummocky topography to periglacial features and to other features indicating the absence of glacier ice outside their limits, and the very clear lateral and terminal moraines associated with some of the fresh hummocky drift, led Sissons and Grant to correlate the fresh deposits with the Loch Lomond Readvance. Thus detailed analysis in the Lochnagar area suggests several small ice accumulations in Zone III times within an area of about 100 km^2.

Investigations by Sissons in two other areas in the Scottish Highlands reveal further evidence of the fragmentary development of Loch Lomond Readvance ice in certain regions. In the south-east Grampians mapping of hummocky drift and related features indicates small ice accumulations at the heads of Glen Prosen, Glen Clova, and Glen Esk (Sissons, 1972). In the Gaick Forest region, to the east of the Pass of Drumochter, fresh hummocky drift and associated landforms allowed Sissons (1974b) to reconstruct an ice cap which developed on the Gaick Plateau, with glacier tongues flowing from the plateau into the valleys that dissect it.

However, morphological evidence alone does not determine the age of the hummocky moraine and associated features. The application of dating techniques is required, and in this thesis palynological investigations and radiocarbon dates are relevant to Thompson's (1972) limits for western Perthshire, while Walker (1974, 1975a, 1975b) and Sissons and Walker (1974) have reported data that support the mapped Loch Lomond Readvance limits in the central Grampians (chapter 9). If the Loch Lomond Readvance limits proposed by Sissons (1976a) can be accepted, then it is possible to base important palaeoenvironmental implications on the areal pattern of these limits.

From the detailed investigation of the extent of the Loch Lomond Readvance ice, and from a knowledge of inferred correlated features from other parts of the Scottish mainland, a picture emerges of a firn-line which gradually declined in altitude from east to west, and of terminal glacier features that attained much lower altitudes in western districts than in the east. Several arcuate moraines of supposed Loch Lomond Stadial age lie at sea-level on the west coast. One of these clear terminal moraines was included in studies by Petrie (1970) and Lowe (1970) of the Glen Torridon region, north-west Scotland. This moraine was correlated with the Loch Lomond Readvance as a result of palynological studies in Glen Torridon and neighbouring Glen Shieldaig. Large outwash plains which are built out into the sea at the western ends of lochs Morar, Shiel, Creran, Etive, Linnhe, and at Ballachulish on Loch Leven were probably formed at or close to the limit of the Loch Lomond Readvance in these districts (McCann, 1966). The radiocarbon date from Loch Creran is useful here. In addition, detailed geomorphological mapping of readvance glaciers in the southern part of the Isle of Mull records Loch Lomond Readvance glaciers reaching present sea-level at several locations (Gray and Brooks, 1972). The relevant radiocarbon date from these deposits has been referred to in section 2.

Recent work in Scotland has thus progressed to the stage where, for certain areas, a more intricate representation of the Loch Lomond Readvance clarifies the more general outline advanced by Sissons (1967a). Recent publications also permit an approximation of the extent of the Loch Lomond Readvance in other parts of the British Isles. Relevant studies suggest very limited glaciated areas confined to the mountains of the Lake District, north Wales, and the Southern Uplands of Scotland, while little published evidence of an equivalent readvance of ice has been reported from Ireland so far.

From a study of fresh morainic drift in the Lake District, often including clear terminal moraines, Manley was able not only to infer a regional development of isolated ice caps and corrie and valley glaciers, but was also able to compute suggested climatic and glaciological parameters from these data (Manley, 1959). He proposed that the wettest districts in the centre of the area possessed a "post-Alleröd" regional snow-line averaging about 1600 ft. (490 m), and that the snow-line rose towards the north-eastern part of the district by about 400 ft. (120 m). This hypothesis of ice limited to high corries and upland basins, and selectively so, is supported by later palynological studies where Late-glacial sediments have been found in tarns at over 500 m in altitude (Pennington, 1964).

Studies in north Wales suggest very restricted ice coverage during the Loch Lomond Stadial, with ice again limited to very high favourable source areas. These conclusions are based partly on palynological studies, where again Lateglacial deposits are reported from basins of high elevation (Seddon, 1957, 1962; Crabtree, 1972), and partly on morphological studies (Unwin, 1973, 1975). Palynological studies in the western part of the Southern Uplands suggest a very fragmentary development of Loch Lomond Readvance glaciers (Moar, 1969a), but the complementary detailed geomorphological investigation that is required has only recently begun.

4. DEVELOPMENT OF THE VEGETATION DURING THE LATEGLACIAL

The first demonstration of a subdivision of the Lateglacial period in the British Isles (on a biostratigraphical basis) that could be compared with the succession at the Alleröd type-section in Denmark was at a site at Ballybetagh in the Wicklow Mountains of Ireland (Jessen and Farrington, 1938). Lake muds found on the floor of a shallow valley were rich in the remains of the Giant Irish Deer (Megaceros sp.) as well as macroscopic remains of tree birch (Betula pubescens) and pollen of pine. These deposits, indicating relatively favourable climatic conditions, contrast with the mineral solifluction deposits that overlie them, the latter providing evidence only for plants of open habitats with a strong representation of plants indicating disturbed soil conditions. Jessen and Farrington established a three-fold subdivision of the Lateglacial stratigraphy at Ballybetagh, corresponding to a cold Zone I, a mild interstadial (Zone II, the Alleröd), and a cold Zone III.

Following this classic work in Ireland recognition of this three-fold division of Lateglacial stratigraphical units was established at a number of sites in the British Isles, and there gradually emerged quite a detailed picture of the character of the regional vegetational response to the Lateglacial oscillation of climate. The 'Lateglacial Period' became loosely defined as that period corresponding to the biostratigraphical zones I, II, and III, defined by Jessen (1949) and by Godwin (1956), and hereafter referred to as the Jessen-Godwin pollen zones. A detailed account of the development of this kind of analysis in historical context is impossible here, but a brief account of the general progress in defining the different regional responses is necessary.

Throughout the Lateglacial period, and especially in Jessen-Godwin Zones I and III, there thrived many plant species that are today characteristic of open habitats. Included in typical plant assemblages are grasses, sedges, heliophytic herbs, and various shrubs (especially Salix and Empetrum). Associated with such assemblages were plants that are characteristic today of disturbed soils and base-rich conditions. Typical Lateglacial vegetation associations are thus very similar in composition to colonisation associations in newly deglaciated regions today (Persson, 1964; Viereck, 1966; Molenaar, 1968), and to montane vegetation refugia described in locations in Britain above the tree-line (Tansley, 1949; Pearsall, 1950; Pigott and Walters, 1954). Other situations where many of these plants can thrive in present-day British environments are those areas subject to sudden soil disturbance, such as major landslip formations (Franks and Johnson, 1964).

In addition, calcicoles are common members of the Lateglacial flora. Plant associations described for highly calcareous localities, as for instance areas of serpentine outcrops and serpentine debris in Scotland (Spence, 1957; Proctor and Woodell, 1971) and the extremely base-rich mountain "flush" flora described by Tansley (1949), include several plants that are typically well represented in Lateglacial pollen diagrams.

The plants involved are common members of the Arctic-Alpine and Continental Northern plant classes (sensu Matthews, 1937), including herbaceous species of Rumex, Artemisia, Armeria, Thalictrum, Campanula, Epilobium, Galium, Plantago, Polygonum, Succisa, Valeriana, Koenigia; the Clubmoss fern Selaginella; the Fir Clubmoss, Lycopodium selago; and common shrub species include willows, juniper, Betula nana, rowan, crowberry (Empetrum nigrum), the Rock-roses (Helianthemum), and occasionally

Sea Buckthorn (Hippophäe rhamnoides). A Lateglacial climatic oscillation has been interpreted from indications of the development of a closed cover of vegetation, with an obvious relative increase in more thermophilous plants, corresponding to Jessen-Godwin Zone II, followed by a return to open conditions in Jessen-Godwin Zone III, which involved the re-establishment of the colonisation flora characteristic of Zone I.

In accordance with the changes in vegetational composition, lithological changes also record Lateglacial environmental changes. Zone I deposits are characterised by an extremely minerogenic deposit, sometimes silt or clay but more often sand or coarser materials towards the base. An organic-rich deposit corresponds to Zone II, represented by gyttja (an organic-rich sediment reflecting relatively eutrophic conditions - Faegri and Iversen, 1964) in lake deposits, or by mud or peat. There is a return to minerogenic sediments in conjunction with Zone III vegetation assemblages, for accompanying the recession in vegetation and disturbance of soils was an increased influx (into basins) of clay deposits, reflecting the harsher climatic environment of the Loch Lomond Stadial.

The close harmony between lithological boundaries and significant changes in pollen spectra, and the overall recognition of a typical Lateglacial vegetational sequence that especially included a characteristic Betula pollen curve (the majority of British Lateglacial pollen diagrams portrayed a clearly marked Betula peak in Jessen-Godwin Zone II followed by its virtual disappearance in Zone III) had two important consequences governing analytical interpretations of biostratigraphical data. Firstly, the clear stratigraphical sequence with accompanying marked fluctuation in arboreal plus shrub pollen totals, usually typified by the Betula pollen curve, became the accepted norm for the recognition of the presence of Lateglacial sediments. Secondly, until as recently as 1970, there was an almost tacit assumption that the biostratigraphical boundaries corresponded almost exactly to major changes in climatic conditions, though in some published works a degree of non-correspondence between biotic and lithological boundaries was inferred. The Jessen-Godwin sequence of pollen zones was interpreted as indicating a cold-warm-cold climatic oscillation in accordance with the often clearly delimited lithological boundaries.

This interpretation, and its erroneous assumptions, are discussed in more detail in chapters 5, 8 and 9. However, features that are basically dependent on the pollen frequencies themselves will now be considered as an introduction to the difficulties encountered in assessing Lateglacial pollen diagrams.

The question must be raised as to what extent the pollen percentages of tree and shrub species actually reflect the undoubted presence of such trees and shrubs in a particular locality, and to what extent they reflect the relative amount of tree or shrub cover during Lateglacial times. This factor is particularly pertinent when considering the relative degree of closed vegetation cover that may have developed in the Zone II amelioration phase. Recent studies in present-day Arctic tundra regions reveal high pollen frequencies of wind-transported tree pollen in areas far outside forest limits, especially pollen of Betula and Pinus, and suggest this factor as an important source of error in interpretations of Lateglacial palynological data (Nichols, 1970). The importance of this source of error, and an idea of the distances involved, are expressed in the recent study of this aspect of pollen dispersal based in the Shetland Islands (Tyldesley, 1973a, b, c). Tyldesley demonstrated that tree pollen are represented significantly in surface samples from these presently treeless islands, and that all of the tree pollen recorded can be accounted for by measured values of tree pollen influx that is supplied to the Shetlands by long-distance wind transport.

The problems that arise in forestless and partly forested areas are best explained in the words of Faegri and Iversen (1964, p.118):

> "With increasing distance from the forest the importance of long-distance pollen increases, and at a sufficient distance, some 10 km from the nearest forest, all AP must be counted as belonging to that category. This is where difficulties arise: the same pollen type may, even in the same diagram, sometimes be produced locally and indicate a warmth period and - in other diagram zones - be carried from a long distance and indicate absence of forest, i.e. unfavourable conditions."

Faegri and Iversen quote the well-known works of Aario (1940, 1944) who, in his studies of pollen representation in present-day vegetation zones in Finland, demonstrated that the *Pinus* pollen representation falls from 80% of arboreal pollen (AP) in the south to 50% AP at the northern end of the pine area and further to 20% in the birch belt. It then rises again to 80% in the AP diagram of the treeless tundra zone. In a diagram based on total land pollen this secondary rise would naturally be suppressed, but the important factor to note is that Aario recorded significant values of *Betula* and *Pinus* throughout the tundra zones, often far outside the limit of forested regions.

Pennington (1970) maintained that most of the *Betula* pollen recorded in many Lateglacial pollen diagrams of northern Britain is in fact of the shrub species *Betula nana*, and that nearly all of the recorded *Pinus* grains resulted from long-distance transport. Vasari and Vasari (1968) suggest that in order to infer the presence of pine in a regional context a continued frequency of *Pinus* pollen in excess of 10% must be present. More recent work from the Glen Esk-Mount Keen district suggests Vasari and Vasari's value to be too conservative (W.W. Newey, unpublished). Taking all of the above factors into consideration, and noting that in the majority of Lateglacial pollen diagrams from northern England and Scotland the arboreal pollen frequencies rarely exceed 50% of total land pollen, it is concluded that great caution is required in any theoretical account of the regional development of woodland in Lateglacial times.

These suggested limitations in the value of pollen frequency data must be balanced against the growing number of finds of macrofossil remains of trees in Lateglacial deposits. Vasari and Vasari (1968) report finding macrofossil evidence for the growth of tree birch in eastern Aberdeenshire from Zone I onwards, whilst at Corstorphine (Edinburgh) only evidence for Betula nana is recorded (Newey, 1970). The evidence of fruits and catkin-scales suggests a major expansion of Betula pubescens in the Lake District in Alleröd times, with the added presence of the more thermophilous Betula pendula in the southern part of the Lake District (Pennington, 1947; Franks and Pennington, 1961; Walker, 1966; Pennington, 1970). It would appear, therefore, that the increased frequency of Betula pollen in northern Britain in Alleröd times is related to a real increase in the number of birch trees present in these districts, rather than the mere reflection of abundant pollen dispersal from woodland in more southerly latitudes.

The evidence for the actual presence of pine woods in the Lateglacial does not have such a sound basis. The recorded find of 2 pine needles in Alleröd deposits in Aberdeenshire (Vasari and Vasari, 1968) contrasts with the hypothesis that 10% pollen frequencies of Pinus are required to indicate the plant's presence in a regional context. There is little evidence for the growth of pine in northern districts of Britain during the Lateglacial, but it is quite definitely considered to have been present in areas of southern England where constant values of pine pollen in excess of 15% of total land pollen have been found in Alleröd deposits (Godwin, 1956, 1975).

In order to resolve the macrofossil and microfossil evidence, where on the one hand the presence of tree and shrub species is positively ascertained, but where on the other hand pollen frequencies rarely suggest a closed tree/shrub vegetation during the Lateglacial, one must envisage a vegetation cover characterised by a scatter of birch copses with co-dominant shrubs (mainly willows and juniper) as the maximum development of the vegetation during the Lateglacial in northern Britain. Birch woodland would have flourished locally in areas of particularly favourable aspect. The spread of birch forest, with pine locally interspersed, was much more advanced in southern districts of England.

One would expect that different regions in Britain would reflect the Lateglacial oscillation by different vegetational sequences, taking into consideration the effects of latitude, altitude, local soil factors, aspect, and other environmental controls. Thus a degree of variation is to be observed between Lateglacial pollen diagrams from northern Scotland and those from southern England. It is interesting to note, however, that the profile from Hawk's Tor in Cornwall, one of the first Lateglacial sites in England to be investigated, exhibits the presence of pollen of such characteristic Lateglacial plants as Betula nana, Salix herbacea, Thalictrum alpinum, Artemisia, Armeria and Helianthemum, as well as spores of Selaginella, throughout the Lateglacial deposits (Conolly, et al. 1950). Some uniformity in Lateglacial pollen diagrams is apparent in the range of the species recorded, and regional differences lie mainly in the relative representation of trees and shrubs.

At Hawk's Tor the only tree genera to be recorded for the maximum development of vegetation during the Lateglacial amelioration, even at such a southerly latitude, consist of Betula, Pinus and Salix, and throughout Zone II these trees appear to have formed an open and discontinuous cover allowing a significant representation of relatively heliophytic species. The development of vegetation in the Alleröd in southern England was thus of a woodland assemblage which is characteristic of northernmost Britain in present-day distribution (Godwin, 1956, 1964), but, due to the time factor or to a temperature control, or to a combination of both, a maximum forest density was not achieved. In the post-Alleröd sediments at Hawk's Tor the typical Lateglacial flora and the disturbed gravelly soils that overlie the Zone II muds provide very strong evidence for climatic severity in a region of some considerable distance from presumed areas of glacial activity during the Loch Lomond Readvance.

In north-west England Pennington (1970) suggests from palynological data that a clearly recognisable altitudinal control affected the spread of tree birches during the Alleröd. It is then concluded that north-west

England was near to the northward margin of the general distribution of birch woodland. Similarly Seddon (1962) claimed that North Wales occupied a critical position in relation to the distribution of birch during the Lateglacial. This conclusion was based on analyses of sediments at two sites that demonstrate an unusual clarity in the Lateglacial oscillation (sharp fluctuations in the Betula curves). In Yorkshire there was a variable response to the Lateglacial climatic amelioration which also indicates that this area lay close to the northward margin of birch woodland. A forested Jessen-Godwin Zone II vegetation at Tadcaster (Bartley, 1962) contrasts with the almost complete absence of forest in other Yorkshire districts (Bartley, 1966). The presence of Juniperus pollen and its increased values in Zone II spectra gives added value to the conclusions based on the Betula pollen data, for records of Juniperus pollen are interpreted as reliable indication of the presence of juniper shrubs close to a particular site (Van der Hammen, 1951; Berglund, 1966).

As well as the assumption of a northward margin of birch forest, based on the concept of a north-south gradient of relative birch cover, Birks (1965) identified an east-west gradient in his published Lateglacial descriptions. The low arboreal pollen counts throughout the Lateglacial at sites in Cheshire and Lancashire are also characteristic of sites in Cumberland, North Wales, Ireland and Scotland, and Birks compared these sites with those with much higher arboreal values in eastern England and East Anglia (Walker and Godwin, 1954) and on the European mainland. The cause of such a gradient may have been the increased oceanity in western districts, and Birks suggested that the major limiting factor may have been the depressed summer temperature. Alternatively, it has been suggested that exposure to continental winter influences may have inhibited tree growth in the east of Scotland during the Lateglacial (Coope, 1968; Newey, 1970). In tracing the pattern of relative woodland and shrub density in the Lateglacial period there is the major difficulty of distinguishing

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In contrast to English data, pollen diagrams from south-west Scotland reveal that the outstanding characteristic of the vegetation history of this region was the extremely open herbaceous communities throughout the Lateglacial, with a very slow spread of birch woodland even into the early part of the Flandrian (Moar, 1969a). Moar's investigations show that the plant cover could not have been complete in the district during any part of the Lateglacial, nor could the soil have been stable, for there is a continued presence of a minerogenic fraction in Zone II deposits, and significant representations of pollen of plants of open, unstable habitat, and of raw, base-rich soils.

In a review of available Scottish diagrams Moar (op. cit.) concluded that climatic amelioration during the Lateglacial was expressed by an increased density of the dominantly herbaceous vegetation and that no influx of birch forest occurred. This increased density of vegetation is expressed differently in northern and southern sites in Scotland; in northern districts Empetrum and Juniperus heathlands spread rapidly in contrast to the increased stability of grasslands in southern Scotland. Both grasslands and heath communities were important in both areas however. Other evidence of Lateglacial vegetational development in north-west Scotland is in agreement with these general conclusions (Pennington and Lishman, 1971; Pennington et al., 1972).

Palaeobotanical evidence from Whitrig Bog in Berwickshire indicates the development of a higher tree pollen frequency and a richer shrub vegetation during the Lateglacial than in other Scottish sites (Mitchell, 1948; Conolly, 1961). Tree-birch fruits testify to the actual presence of Betula at this locality. Analyses of the development of vegetation at Whitrig Bog are similar in many respects to those relating to typical sites in northern England, and this would seem to suggest the possible northern encroachment of birch woodland into a favourable sheltered locality in southern Scotland.

Lateglacial vegetational developments in Scotland, particularly in the Highlands, are described in more detail in chapter 9. However, in conclusion to this section, it is evident that the growing volume of palaeobotanical data for the Lateglacial in Britain permits, in very general terms, a crude reconstruction of the character of the vegetation cover at different stages of this period. It is suggested that, at the height of the Lateglacial climatic amelioration phase, usually equated with the Alleröd chronozone of continental north-west Europe, (Mangerud et al., 1974; Godwin, 1975; Pennington, 1975), a widespread woodland developed over much of the lower ground of southern, central, and eastern England; woodland, mainly of Betula pubescens, became gradually more fragmentary in nature in northern England, where a strict altitudinal control appears to have been enforced, and where woodland was probably increasingly confined to major valley systems; birch was present in isolated copses only in southern and eastern Scotland; and in western and northern districts of Scotland birch woodland virtually disappeared, to be replaced by dominant heathland and grassland communities. Following this a major vegetational revertence phase can be recognised in all Lateglacial pollen profiles from Britain, most notably in the marked reduction or almost total absence of pollen grains of tree birch and thermophilous shrub species. This phase, in pollen zonations termed Jessen-Godwin Zone III, is equated with the Younger Dryas chronozone of north-west Europe.

However, the interpretation of Lateglacial pollen diagrams is not straightforward and a number of major problems complicate attempts to test the validity of environmental reconstructions and of chronology and correlation. As discussed briefly above, there are problems associated with interpretations of pollen assemblages as a basis for the reconstruction of vegetational developments. In addition, there is growing evidence to suggest that biostratigraphical boundaries, originally thought to be more or less synchronous, are significantly time-transgressive within the British Isles, and recent coleopteran evidence has enforced a major reappraisal of interpretations of Lateglacial climatic developments previously based solely on palaeobotanical evidence (Coope, 1975). Detailed discussions of each of these problems are provided in several chapters in this thesis.

5. THE LATEGLACIAL CLIMATE: INFERENCES BASED ON PALAEOBOTANICAL DATA

During the preparation of this thesis some of the general concepts regarding climatic development during the Lateglacial were in a considerable state of flux due to some important new discoveries from palaeozoological investigations (Coope and Brophy, 1972), from the application of absolute pollen counting techniques (Pennington and Bonny, 1970; Pennington, 1975, 1977), and from investigations involving combined palynological and chemical analyses of sediments (Pennington and Lishman, 1971; Pennington et al., 1972). The results of each of these techniques in recent enquiries require some modification of interpretations based on the traditional Lateglacial sequence, and this problematical theme is further discussed in chapters 9 and 10.

These investigations highlight the fundamental problem that any attempt to deduce climatic indices from palynological data must first consider the value of relative frequency data in reflecting the areal representation of individual species, and, in the light of conclusions based mainly on the studies of Coope and Brophy, must also consider to what extent vegetational responses actually parallel the climatic fluctuations that instigated them. There appears to have been a significant time-lag in the vegetational expression of climatic changes probably caused by the time required for pedogenesis and for the migration (immigration) of plant species.

Several attempts have been made to infer Lateglacial climatic parameters, both from the character of typical vegetation assemblages and from the presence of recognised indicator species. There are, however, serious limitations to such attempts. For instance, Walker (1966) inferred a temperature range for the post-Alleröd climatic deterioration from the character of plant assemblages and the presence of indicator species in the lower regions of north-west England. His judgements were based mainly on the presence of species indicating arctic conditions, such as Salix herbacea, and Koenigia islandica, the latter being especially well suited to studies of maximum (lethal) temperatures (Dahl, 1951, 1963). Walker concluded that winter temperatures regularly fell to -2^{o}C but rarely below -8^{o}C, and summer temperatures regularly rose to 10^{o}C and frequently rose to 14^{o}C in favoured localities. However, plant distributions are by no means dependent solely on thermal controls, and the relative oceanity or continentality of climate must have been a critical factor in Lateglacial times. Dahl's original studies (1951, 1963) admit the limitations of conclusions based on isothermic data, for much is desired in the way of autecological investigations of the relative importance of soil moisture, base-status, light factors and other factors in comparison to the limiting effect of the thermal regime.

The difficulty of interpreting the ecological factors that controlled plant distributions as revealed by palaeobotanical studies is stressed by Conolly (1961, p.59):

> "In the more extreme oceanic regimes maximum summer temperature may be replaced as a limiting factor by other components of oceanity such as excessive dampness and high winds. A single factor is not necessarily limiting throughout the range of a species and some modification is not unlikely. One must accept a multi-factorial basis for the concept of oceanity and continentality."

Conolly provides the example of regarding individual plants as indicating snow-patch community habitats as an instance of misinterpretation in applying ecological judgement to past records. Species that are decidedly chionophilous in some situations and in mildly oceanic conditions can be limited by exposure only in other situations and can be less characteristic of snow-bed communities in more oceanic climates. Further, a recent attempt to reveal the relative oceanic-continental nature of different parts of the British Isles during the Lateglacial through the distribution and local importance of Empetrum in pollen records met with great difficulty, for the distribution of Empetrum is to some extent governed by the local importance of birch cover, and is also dependent on other environmental factors affecting its range (Brown, 1971).

Vasari and Vasari (1968) have concluded from comparisons of Lateglacial vegetation assemblages that the fossil assemblages of Zone III indicate a much more severe climate than those of Zone I. Diatom assemblages related to their pollen investigations in Aberdeenshire were interpreted as indicating that the climate of Zone I was not arctic in character, and in fact little difference between the climate of the later parts of Zone I and that of Zone II could be established on the basis of diatom studies. Vasari and Vasari further proposed that the Zone III period was rather more oceanic than earlier Lateglacial phases, and support for the concept of an oceanic Zone III is found in Manley's (1959) description of the Zone III climate proposed for the Lake District where "... the average annual precipitation ... was nearly as great as today ... As the air was colder ... it seems fair to suggest that the climate was more unsettled than today and that precipitation fell more often. In virtue of the low temperature and high precipitation, the air would be prevailingly damp, with much low cloud at all seasons" (p.206).

Manley's deductions are based in part on glaciological studies in north-west England, partly on the presence of tree birches in the Windermere region, and are partly intuitive (Manley, 1949, 1951, 1952, 1959). Further, Vasari and Vasari's (1968) conclusions are based mainly on sites from the relatively continental eastern districts of Scotland, and their conclusions, if valid, may only have a restricted regional application. Sissons and Sutherland (1976), on the basis of detailed analyses of reconstructed firn-line altitudes for the Loch Lomond Readvance glaciers in the south-east Grampians, have concluded that total precipitation values during the Loch Lomond Stadial were probably similar to today, though differently spatially distributed.

In addition to conclusions based on the presence of individual species and certain plant assemblages, Birks (1973) speculates about climatic development during the Lateglacial in Skye on the basis of the absence of Corylus avellana. Pollen grains of this species are virtually absent from the Lateglacial pollen record of Skye, and are always insignificant in diagrams from other parts of the British Isles. In view of the present climatic tolerance of hazel and its occurrence on a wide variety of soil types in Scotland, Birks finds it inconceivable that conditions were not suitable for its growth and flowering, especially during the period equated with the Alleröd interstadial, which was apparently favourable to the development of tree birch. Birks claims that this remains one of the fundamental problems in the task of reconstructing the Lateglacial environment, and suggests that

> "... the climate during Late-Devensian times was radically different from any known today in some respect critical to hazel but not to birch. For example, the spring and summer temperatures in the Late-Devensian may have been as high as at present but with a greater minimum and maximum temperature range and a higher incidence of spring frosts than exists today anywhere within the range of Corylus avellana. Such a climatic regime may have favoured birch and other trees and shrubs, and yet it may have failed to reach some critical threshold necessary for the establishment and survival of hazel" (pp.381-2).

The evaluation of Lateglacial climatic indices from palaeobotanical evidence remains a speculative procedure. The relationship between individual species and specific ecological factors is too little understood to allow other than very tentative generalisations. Precise evaluation of climatic parameters for the Lateglacial, and of the magnitude of change of climatic parameters, is not yet possible. It is, however, widely accepted that in some way climatic conditions were highly critical during this period, and one would thus expect that any variation in other ecological variables would have resulted in quite marked and possibly abrupt variation in vegetation. This would have been especially true within the highland areas of Britain where the critical nature of ecological factors would have been most marked.

6. A BRIEF ACCOUNT OF FLANDRIAN VEGETATIONAL AND CLIMATIC DEVELOPMENTS

Before the development of pollen analysis the botanists Blytt and Sernander established a five-fold classification of postglacial climate recognised from macrofossil evidence in peat bogs and lake deposits (Pennington, 1969). The Blytt and Sernander periods, and subsequently determined average radiocarbon dates for their boundaries, can be briefly characterised as follows:-

	(Stage)	(Climate)	(Years B.P.)
5)	SUB-ATLANTIC	cold and wet; Oceanic climate	after 2450
4)	SUB-BOREAL	warm and dry; Continental	4950 - 2450
3)	ATLANTIC	warm and wet; Oceanic	7450 - 4950
2)	BOREAL	warm and dry	9550 - 7450
1)	PRE-BOREAL	sub-arctic	10250 - 9550

Attempted applications of the Blytt and Sernander periods to subsequent detailed palynological investigations in other parts of Europe outside Scandinavia proved difficult and Von Post, one of the early pioneers in palynological research, advocated a simpler outline of postglacial time, with a three-fold division, thus:

(1) Stage of approach of warm period characterised by the appearance and first increase of relatively thermophilous trees of different kinds ('terminocratic phase');

(2) The stage of culmination of these elements ('mediocratic');

(3) A stage of decrease of the characteristic trees of the warm period and the return of the dominant forest constituents of the present day ('terminocratic').

Both Von Post's and Blytt and Sernander's schemes (and all subsequent studies of postglacial development in north-west Europe) recognise a "mid-postglacial" climatic optimum, as revealed through vegetational developments, which terminated at about 5000 B.P., and during which period tree species more thermophilous than the present day forest cover thrived in all areas in north-west Europe. The present thesis is mainly concerned with postglacial vegetational developments until the climatic optimum, where attention is focused on immigration and competition, avoiding the different suite of complicated problems involved in interpretations of post-climatic optimum vegetational and climatic history.

TABLE 1 Godwin's (1940) subdivision of Flandrian vegetational history of the British Isles compared with vegetational developments in Ireland and N. Scotland (after Godwin, 1975)

Radiocarbon Years (B.P.)	Godwin Pollen Zone	VEGETATION Ireland	VEGETATION Br. Isles	N. Scotland
0				
2000	VIII	Alder-Birch-Oak	ALDER-BIRCH-OAK (BEECH)	Lightly wooded heath
4000	VIIb	Alder-Oak	ALDER-OAK-LIME	Pine-Birch-Alder
		(Elm decline)		
6000	VIIa	Alder-Oak-Elm-Pine	ALDER-OAK-ELM-LIME	
8000	c VIb a	Hazel-Pine	PINE-HAZEL	Pine-Birch B-H
	V	H-B	H-B-P	Juniper-Empetrum
10000	IV	Birch	BIRCH-(PINE)	

LOCH LOMOND STADIAL (Zone III)

H = Hazel
B = Birch
P = Pine

Detailed analyses of the development of vegetation in the British Isles resulted in a zonation scheme of subdivisions of climatic evolution that were broadly comparable to Blytt and Sernander's basic scheme (Jessen, 1949;

Godwin, 1940, 1956). Godwin's six-fold subdivision of Flandrian time in the British Isles (Table 1) was widely accepted as the typical outline which could be applied in all British investigations, and in 1957 a detailed study of the widely used numerical postglacial zonation system from a continuous sequence of organic deposits at Scaleby Moss (Cumberland) purported to show that the characteristic features of postglacial pollen diagrams are, over a large part of north-west Europe, "probably broadly synchronous" (Godwin et al., 1957).

A similar detailed study at Red Moss in Lancashire provided dates in good agreement with some of those from Scaleby Moss, but in general the mean ages at Red Moss gave the impression of being slightly younger than the Scaleby Moss dates (Hibbert et al., 1971). The importance of the Red Moss investigation, however, is in the discovery of the time-transgressive nature of some of the features of postglacial development, formerly accepted as broadly synchronous in a north-west European context. The time-transgressive nature of diagnostic pollen zone boundaries was even evident from a comparison of the British dates alone (assuming the radiocarbon dates to be valid). In addition, time-transgressive pollen zone boundaries have recently been advocated in comparisons of vegetational development between England and northern Scotland (Pennington and Lishman, 1971; Birks 1973).

Though the general pattern of the Godwinian zonation scheme can be recognised in many districts throughout Britain, there is some serious doubt as to the validity of employing this scheme alone in any comparative inter-regional analysis due to the non-synchronous nature of key features used to formulate the scheme. The system is gradually being replaced by a chronostratigraphic approach in the analysis of postglacial vegetational development. Pollen diagrams from a given location are assigned local zonation divisions based on the recognition of local pollen assemblage zones and these are later incorporated into a regional synthesis of several diagrams giving regional assemblage zones. Ultimately reference radiocarbon dates are established giving a chronostratigraphic outline of development for that region. This general topic will be discussed in a later section dealing with the zonation of the diagrams in this thesis (chapters 7 and 11).

The pollen zonation scheme defined by Godwin for England and Wales has been continuously applied in Scottish investigations until very recently, though often the original definitions were largely disregarded due to differences in the order of appearance of species, and due to the reduced importance in parts of upland and northern Scotland of the more thermophilous tree species. Quercus, Ulmus, and Alnus play a role of diminishing importance towards northern Britain, and there is little evidence in Scottish pollen diagrams for the presence of Tilia, Fraxinus, or Fagus. A brief account of the general development of vegetation in Scotland will now be given with special emphasis on the earlier periods before the end of the climatic optimum. Any reference to postglacial numbered zones or names of stages as defined by Godwin are purely for convenience in this brief skeleton survey, and it is recognised that the boundaries of the various stages are not synchronous and that there is strong evidence for time-lag and variation in Scottish palaeobotanical studies.

At the onset of the Flandrian period in Scotland vegetational reaction to climatic improvement resulted in the recurrence of the species assemblages characteristic of Jessen-Godwin Zone II, with successive maxima in Empetrum, Juniperus, and Betula. This is unlike the development in England and Wales where a speedy attainment of dominant birch woodland occurred, or where mixed birch and pine forest developed.

In his pollen diagrams from central Scotland Donner (1957) could see no significant differences between the non-tree pollen of Zone III and Zone IV, and he therefore introduced a new zone for application to Scottish material, a zone of transition (Zone "III-IV") between the open, herbaceous character of Zone III and the dominant birch forest that characterises

Zone IV. This slow immigration of birch woodland in early Flandrian times ('Pre-Boreal' period) is supported by the studies of Vasari and Vasari (1968). They recognised the existence of three types of vegetation characterising the III-IV transition period in each of the three different geographical regions of Scotland that they studied:-

1. In eastern coastal districts (eastern Aberdeenshire) birch trees were much more abundant than elsewhere in Scotland, but even there the prevailing vegetation could still be described as "park tundra", where a relatively open birch woodland was in existence, with _Juniperus_ present as a significant component.
2. In the Isle of Skye (and in western districts of Scotland as a whole) the landscape was still almost treeless, with willows and juniper maintaining relative importance later into the postglacial.
3. An intermediate type of Pre-Boreal vegetation between types 1 and 2 is reflected in the pollen diagrams from the Southern Grampians (see also Donner, 1958, 1962).

There was thus an east-west and a north-south gradient in relative vegetational development as was evident in the pattern of development in Zone II times, and this relative areal differentiation in the effects of environmental conditions is also reflected in the lithological characteristics of the sediments. Vasari and Vasari point out that minerogenic inwash into basins terminated at the end of Zone III in eastern Scottish districts, but a minerogenic component is evident throughout the III-IV transition sediments in those sites investigated in the Isle of Skye.

Moar's investigations in Scotland also established a transition phase where, in those sites investigated in south-west Scotland, _Salix_ and _Juniperus_ were locally dominant (Moar, 1969a), and in those sites from farther north this transition period was relatively protracted (Moar, 1969b and c). In these northern sites (Sutherland and the Orkney Isles) _Betula_ did not succeed in establishing a general widespread cover until late in the postglacial, and at no time in the Flandrian period did it achieve the domination of the landscape exhibited in other regions of Scotland.

A birch forest cover was established over most of lowland Scotland by Boreal times, and this was quickly followed by the next important development in the vegetational succession to have widespread effect, the arrival of Corylus (hazel). "The advancing hazel not only conquered some of the previously forestless ground, but it also attacked the light birch-juniper forests replacing them to some degree and becoming especially fatal to juniper which earlier thrived well in the light forests and on open ground" (Vasari and Vasari, 1968, p.79). This approach to domination by hazel appears to have diminished northwards and westwards from the Grampian Mountains. In the pollen diagrams from sites north of the Central Valley Corylus fails to achieve the high frequencies found at sites in south and central Scotland (Durno, 1956, 1957, 1959; Vasari and Vasari, 1968; H.H. Birks, 1970; Pennington et al., 1972).

A long dominant birch-hazel period is a marked characteristic of most Scottish pollen diagrams, and this is especially clear in the more southerly sites and in analyses referring to the southern and eastern fringes of the Grampians. In more northern regions hazel was not quite so effective in immigrating into the light birch-juniper forests, and in the more favourable localities of lowland Scotland the introduction into the Boreal birch-hazel association of Pinus and the more thermophilous deciduous trees was extremely variable.

The arrival of Pinus in the birch-hazel dominated landscape is extremely well marked at some sites in Scotland, especially in localities north of the Grampian Mountains, but is much less so at others. Its history can reveal a short flourish in Boreal times, to be replaced eventually by more thermophilous tree species (Donner, 1957; Durno, 1959), or that it commanded a dominant position in the landscape throughout much of the Flandrian, as at Loch Kinord in the Dee Valley (Vasari and Vasari, 1968). Analyses from the Abernethy Forest region in Inverness-shire show that pine forests became established in the area by about 7000 B.P. and remained dominant in this region until the present day (Birks H.H., 1970; O'Sullivan, 1974).

Pennington (1970) concluded from her observations of the erratic frequencies of Pinus pollen in diagrams from the Lake District that although Betula, Corylus, Ulmus, and Quercus were climatically controlled in this region, and thus developed a pattern of succession similar in outline to Godwin's scheme, Pinus must have been edaphically controlled and did not conform to an ideal pattern in all investigations. Given that edaphic factors, the degree of oceanity or continentality, altitudinal range, and latitudinal range (as expressed in temperature effects and relative distance of regions from source areas in species migration) could effectively control the areal representation of different species as indeed they do today, then the conclusion that the appearance, local domination, and disappearance of individual species are synchronous in two different localities is not a viable one unless reference can be made to some absolute time scale.

The use of a marked increase in the frequency of Alnus pollen to indicate the beginning of the Zone VIIa Atlantic phase in Godwin's scheme is difficult in Scottish pollen diagrams where much variance in the pattern of development of Alnus is experienced, and where it can be established that the immigration of Alnus may have occurred by up to 1000 years later than in England (Pennington et al., 1972). A problem of subdued representation is also met with in considering the importance of Ulmus. The dominant pine forest of the Abernethy Forest region has already been mentioned, and H.H. Birks (1970) concludes from her work in this region that thermophilous deciduous species, such as elm and alder, were rare occurrences throughout the postglacial and did not contest the established dominance of pine.

In some areas south of the Grampians Donner revealed that not only was there a marked Alnus rise indicating, for him, a clear Zone VI-VIIa boundary, but also that the alder was quite common for some time before this period (Donner, 1962). He also recorded a strong representation of Ulmus and Quercus, but a very variable outline in the pattern of representation of Pinus pollen. Donner concluded that although Pinus was present in the Boreal period in the Midland Valley, it quickly gave way to a mixed deciduous forest. In areas north of the Highland Edge, however, Pinus became dominant over deciduous forest elements and in some areas remained so. All the available literature points to the general area of the Highland Edge, the southern fringes of the Grampian Mountains, as being a critical locality in the reconstruction of the vegetational history of Scotland.

From investigations of peat deposits in the Pentland and Moorfoot Hills, to the south of Edinburgh, Newey (1968) was able to distinguish a general sequence of forest development that very much resembled that of eastern England, and he therefore applied the Godwinian zonation scheme to the relevant pollen diagrams. The pollen frequencies for Ulmus and Quercus are much higher in lowland sites of south-east Scotland than they are in other districts of Scotland, and Newey suggests that this is probably the result of more favourable soil and climatic conditions in the south-east. More difficulty is encountered in lowland sites of south-west Scotland, however, when attempting to apply the standard zonation scheme. Because of obvious differences in vegetation development Moar (1969a) devised a system of zones more appropriate for his Scottish pollen diagrams.

Nevertheless there is evidence of a pronounced phase of broad-leaved deciduous forest in parts of central and southern Scotland where Godwin's zonation scheme can be applied without difficulty (Newey, 1968; Brooks, 1976), and this is discussed in more detail in chapter 12, where evidence for early Flandrian vegetation developments is reviewed.

As a general conclusion from published works so far, it is now widely accepted that the strict definitions of the British standard pollen zonation scheme devised by Godwin cannot be applied to the majority of Scottish pollen diagrams, with the possible exception of the south-east region. It is only to be expected that the effects of various factors controlling the distribution of plant species in the British Isles (migration rates, climatic factors, soil status, altitudinal control) would be most critical in the relatively harsher climate of the more northerly latitudes, and it would appear that the southern districts of the Grampian Mountains held a most critical position in this respect. Regional variation in the potential climax forest vegetation of the present day in the British Isles is a well documented field of botanical interest (Tansley, 1949; Pearsall, 1950; McVean and Ratcliffe, 1962; Burnett, various papers, 1964; Pears, 1968), and it is a fairly safe assumption that such characteristic regional differences operated in the past. The restrictions of the standard scheme, in a Scottish context, are especially noticeable in attempts to apply the three-fold subdivision to Zone VI which Godwin was able to recognise through the orderly immigration of thermophilous tree species in eastern England, and which he interpreted as indicating generally increasing climatic warmth.

Following the so-called climatic optimum, the termination of which is expressed by the end of the Zone VIIa Atlantic Period in the standard scheme, marked by a sharp decline in Ulmus pollen frequencies in the pollen diagrams of most regions in England, a widespread and gradual climatic deterioration appears to have occurred throughout the British Isles. Decreasing temperature is thought to be indicated by a return to dominance of the pollen of the less thermophilous genera, Betula and Pinus, and a tendency to more open forest conditions. Investigations of the later parts of the postglacial vegetational history,are, however, complicated by the difficulties of separating the causal effects of oceanity and decreasing temperature in this period of deteriorating climate, by the impact of a new factor governing vegetational pattern - the deliberate actions of man - and by the controversial theories which surround individual facets such as the Elm Decline. Because the bulk of the investigations in the present thesis are directed towards the initial 'terminocratic' phase and the establishment in Scotland of the climax 'mediocratic' vegetation, a resumé of the post-mediocratic history is not presented here.

CHAPTER 2

The Study Area - Sites of Investigation in Southern Perthshire

1. THE AREA OF INVESTIGATION

The aims of this investigation are primarily directed towards the testing of hypotheses concerning the Lateglacial period and the transitional phase between the Lateglacial and the Flandrian Stage, and towards a further understanding of historical events within this period in Scotland. A sound and logical basis for such a study would be to apply the relevant stratigraphical and palaeobotanical studies to an area for which detailed geomorphological investigations have already been completed. The stratigraphical investigations reported in this thesis are based in an area for which detailed morphological data were readily available, the area having been studied by Thompson (1972). His study provides an outline of the morphological effects of Late Devensian glaciation in this region, an outline which bears logical relationships to other similar detailed studies in adjacent areas to the south and east.

The extensive area covered in Thompson's thesis includes the areas around Callander and Crieff in the south to Glen Garry in the north, and stretches westwards to Rannoch Moor from lower Glen Almond and the upland to the west of Strathtay. This represents a large, mainly mountainous region to the north of the Highland Boundary Fault, an area which is bordered to the south by Strathallan and Strathearn, and which includes several major valley systems: Glen Garry-Glen Errochty; the Loch Voil and Loch Earn basins; the Loch Rannoch and Loch Tummel basins; Glen Almond; Glen Artney; the Trossachs and Teith valleys; and part of Rannoch Moor. Within this area (Figs. 1 and 5) are some of the eastern limits of Loch Lomond Readvance glaciers proposed by Sissons (1967a), and to the south and east in the broad lowlands of Strathearn, Strathallan, and the upper Forth Valley, are to be found the characteristic large and abundant fluvioglacial features produced by the stagnating Late Devensian ice-sheet that preceded the Loch Lomond Readvance.

On the basis of the recognition of 'fresh hummocky drift' (see Sissons or Thompson for detailed accounts and full definitions), which is assumed to be a characteristic feature of the Loch Lomond Readvance, and which contrasts markedly with features of older and more widespread glaciation, Thompson proposed limit-lines for the Loch Lomond Readvance (Zone III glaciation) in this area. A simplified outline of these limit-lines is presented in Fig. 5. The results of his investigation suggest that all but three of the major valleys within this region were interlinked by a continuous spread of glacier ice during the last stage of glaciation, the three exceptions being Glen Almond, Glen Artney, and Glen Garry. In the latter valleys small isolated valley glaciers developed.

Thompson noted a degree of uniformity in the drift deposits within his mapped limit-lines, both in morphology and in basic constituents. The major conclusions that he draws from his research in this area are:-

1. that the fresh hummocky drift in each valley is the result of one stage of glaciation;
2. that this was the last stage of glaciation in Scotland, occurring not later than and probably during the Loch Lomond Stadial;
3. that this last stage was a readvance rather than a reactivation of the last ice-sheet.

Though the pattern of development suggested by these conclusions may appear to be logical, acceptance of the basic thesis clearly depends on additional evidence from other forms of enquiry. Similarity in appearance does not necessarily imply similarity in age. If, however, such a thesis and the premises upon which it depends could be accepted, then this type of investigation would provide much useful information for considerations of the extent and duration of the Loch Lomond Readvance.

A critical location within the area studied by Thompson is that of the Teith Valley, especially in the environs of Callander. Much of the detailed analysis of the present thesis refers to this area, and thus a brief account of the sequence of events proposed by Thompson for the locality will now be given. The features referred to are reproduced in simplified form in Fig. 6.

The central and most significant feature in the Callander area is a well marked arcuate end-moraine of which parts are to be found on both sides of the River Teith about 2.5 km south-east of Callander. On the eastern side of the Teith the feature descends from about 100 m in altitude to about 60 m towards the river, and on the west side it gradually ascends north-westwards to about 90 m. This feature is interpreted as indicating the terminal position attained by a readvance of ice, and it occupies a position at the mouth of a Highland valley which is analogous to those of the terminal moraines in the neighbouring Menteith and Loch Lomond basins (Fig. 4).

Beyond the Callander terminal feature, to the south-east, a series of large fluvioglacial forms - kames, eskers, and terraces - are recorded. From a study of the Forth Valley to the south and south-east of the Teith Valley Smith (1965) concluded that these fluvioglacial forms on the edge of the Teith Valley were produced during the stagnation of an ice-sheet of pre-Alleröd age. The lowest terraces within this group of features were subsequently levelled by Thompson and are shown to be related to meltwater activity attributed to the glacier snout at the Callander terminal feature, but other higher terraces in the Lower Teith do not bear a positive relationship to the terminal feature and are to be related to the meltwater activity during ice-sheet decay. This latter suite of terraces was found to be intimately associated with the large kame and esker deposits south-east of the Teith-Keltie confluence. Sections within these terraces exhibit ice-contact structures.

The lower terraces in the Teith valley cut across the kames and eskers related to ice-sheet decay, and if traced up-valley these lower terraces are found to merge with outwash and kame terraces related to the

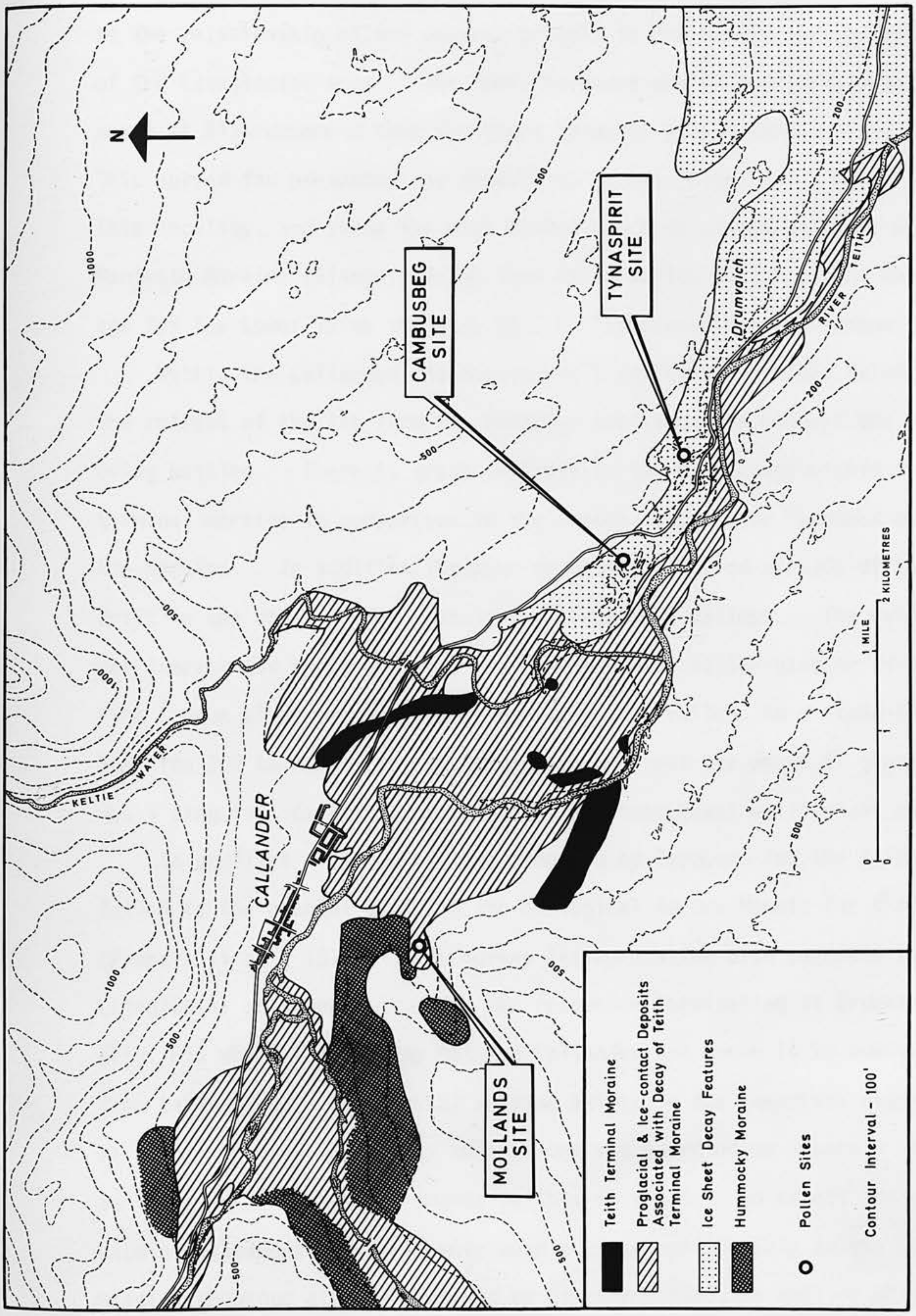


FIGURE 6 Glacial deposits in the Teith Valley (after Thompson, 1972) and location of pollen sites.

terminal feature at Callander. An important characteristic of part of this group of lower terraces created by the outwash of the Teith glacier is the relationship of the outwash gravels to the buried marine deposits of the Lateglacial seas. The lower terraces can be traced down-valley until at Blairdrummond they are found to merge with a large buried fan. This buried fan prevented the deposition of the 'High Buried Beach' at this locality, and since the High Buried Beach is contemporaneous with the Menteith Moraine (Sissons 1967a) then this implies a Loch Lomond Readvance age for the Lower Teith terraces (K.S.R. Thompson, personal communication).

Within the Callander end-moraine is a series of terraces related to the retreat of the ice from the terminal position, the highest one of them being kettled. There is great contrast in the morphology within the terminal moraine in comparison to the smooth large-scale features outside the moraine. In addition Thompson recorded scattered spreads of hummocky drift in the Upper Teith, Lubnaig, and Trossachs valleys. The evidence was interpreted by Thompson as indicating that a valley-glacier advanced from source areas in the Lubnaig and Trossachs valleys to a stand-still position 2.5 km south-east of Callander, and that the phase of glaciation was a singular one with no evidence of any subsequent still-stand positions.

In conflict with the outline proposed by Thompson for the Teith Valley is the account given in the Geological Survey Memoir for that area (Francis <u>et al</u>., 1970). The Survey interpretation also suggests that a Lateglacial readvance occurred, the readvance terminating at Drumvaich (Fig. 6), which lies midway between Callander and Doune (4 km downvalley from Callander). No terminal moraine exists in the immediate environs of Drumvaich, and the Survey conclusions are based on an apparent change in the form of the gravel mounds in this district. In effect the concluding statements in the Memoir bear a close relationship to the outlined glacial sequence already provided by Simpson (1933), an outline which was basically reiterated by Charlesworth in 1955. However, whereas Simpson and Charlesworth were very general in their delimitation of the extent of the readvance glaciation, the 1970 Memoir does give a specific outline of the limit of the readvance, an outline which differs by some 4 km from that proposed by Thompson.

Thompson does not believe that glaciers of the readvance stage could have advanced as far down the Teith Valley as Drumvaich. He rejects the basic thesis of the 1970 Memoir on the grounds of alternative interpretations of some of the morphological features considered in the Memoir, and because of some apparent discrepancies in the data employed. In amplification of the latter objection Thompson points out that some important evidence contained in Smith's thesis (1965) was omitted, and that some of the analyses of particular landforms included in the Memoir are highly questionable. The palynological investigations in the Teith Valley presented in this thesis resolves this conflict in opinion.

Pollen analytical investigations were undertaken with the following aims in mind:

1. to reconstruct the pattern of vegetational development in this part of the Grampians throughout the transitional period from Late Devensian to early Flandrian times;

2. to test the limits of the Loch Lomond Readvance proposed by Thompson for this area;

3. to test the applicability of general theories of Lateglacial climatic, vegetational, and glaciological developments to this area.

This thesis is concerned with the degree of complementation or possible contradiction between vegetational, morphological, and stratigraphical considerations. Much rests on the basic premise first outlined by Donner (1957, 1962) that no evidence for a Lateglacial oscillation in vegetational developments should be found in the basal sediments of basins located within the proposed Loch Lomond Readvance limits, and that evidence for sedimentation of Alleröd age should be found in suitable basins located outside these limits. Sites of investigation were chosen as close to the proposed limit-lines as possible. Basins (usually kettle holes) that are presently infilled by peat were chosen in preference to present-day lochs and lochans in order that the whole surface area could be tested for the deepest sampling points available, thus ensuring that the earliest sediments received by each basin of accumulation were collected for analysis.

It was decided at the start to commence investigations in the southern part of the area studied by Thompson and to work northwards as time would permit. This procedure was chosen for the following reasons:

(a) The crucial position of the Callander terminal feature and other deposits in the Teith Valley in Thompson's thesis. The Callander terminal moraine is the clearest indicator of deposits of Loch Lomond Readvance age in this region.

(b) The availability (in 1970) of published Lateglacial pollen diagrams which could be used for regional comparisons. At that time few pollen diagrams were available for Scottish districts, and the nearest Lateglacial pollen diagram to this part of the Grampians was Donner's site at Loch Mahaick, Perthshire (1958).

(c) The availability of suitable sites within the Teith Valley. This was a known factor because of initial stratigraphical enquiries included in Thompson's data.

2. FIELD SAMPLING TECHNIQUES AND EQUIPMENT

Initial investigations involved the use of Hiller samplers, this being the only type of sampler available to the writer at that time. Subsequent analyses have shown the use of the Hiller sampler to have been far from satisfactory in the sampling of certain sediments. Thus whilst much satisfaction is felt concerning the results of later investigations where use was made of a modified and enlarged Livingstone sampler, or of an enlarged Dachnowski piston sampler, the author must admit to some dissatisfaction with the results of the Hiller sampling equipment employed extensively in the preliminary parts of this research programme. Comparison of the results of the various sampling tools is made occasionally in this thesis, but a summary of this factor, and a discussion of the reservations to be placed on the use of Hiller equipment, is provided in Appendix 2. An account of sampling techniques will now be given in relation to the four different models of sampling equipment employed:-

(a) Hiller sampler (Faegri and Iversen, 1964, p.55)

Two Hiller samplers were used in stratigraphical surveys. A small Hiller with a chamber length of 30 cm and diameter 1.5 cm was used only for the determination of stratigraphical features when the larger model was found to be impracticable. Use of the larger Hiller sampler (chamber length 50 cm; diameter 3.5 cm) was preferred in stratigraphical work, and was essential for use in the collection of samples for pollen counting.

Little difficulty was encountered in penetrating the various sediments of the sites surveyed when using Hiller equipment, with the exception of thick basal clays which proved extremely variable in their resistance to penetration. (See Section 4).

Detailed stratigraphical descriptions were recorded in the field for each site, for facilities permitting the return of undisturbed stratigraphical cores to the laboratory were not available.

The standard field procedure employed when using Hiller equipment was to use two small spatulas to dissect the cores and to abstract small sediment samples from near to the centre of the cores. This was a very tedious procedure in which careful inspection had to be constantly applied in an attempt to prevent contamination that was visibly discernible, and the method usually resulted in individual samples of clay representing 1 cm length of sediment core, and an average corresponding measure in peat of 0.5 cm.

The samples were collected in small glass bottles for their return to the laboratory where they were sealed with wax before storage.

(b) "Russian" sampler (Jowsey, 1966)

This was found to be unsuitable in the sediments at two localities where it was tested. Complete cores could not be obtained from the extremely soft organic muds at the Cambusbeg site (see below), and the amount of flowage (plastic deformation) in the incomplete cores could not be ascertained. The large bulbous nose of this device could not penetrate the Lateglacial sediments at Tynaspirit which are relatively compact, and again at Cambusbeg the soft basal clays, like the Flandrian muds, were not sampled satisfactorily with this equipment.

(c) Enlarged Livingstone piston sampler (Rowley and Dahl 1956)

Use of the Livingstone piston corer was only possible for an extremely short period as this was the property of Prof. Yrjö Vasari of Finland who kindly allowed the use of this equipment during a visit to Scotland in July of 1972. The rather large size of the sampling chamber (length 90 cm; diameter 6 cm) resulted in some difficulty in penetration at the one site where it was employed (Tynaspirit). Eventually, however, cores of 90 cm in length were collected which contained sediments in an exceedingly good state of preservation, and which showed little signs of distortion or compaction.

The cores were extruded from the sampling chamber into plastic half-piping of suitable diameter, and they were then covered by thick adhesive plastic "transpaseal" which rendered them air-tight at all times during storage. The sealed samples were stored in cool dark conditions until opened for analysis or for abstraction of material for radiocarbon dating. The period of storage prior to analysis did not exceed 10 weeks. (Samples were still found to be in a good state of preservation after a full year in storage).

(d) Dachnowski piston sampler (Bouma 1969, pp.311-12) and Abbey Piston Corer

A Dachnowski piston sampler was obtained from Holland in November 1972 with two piston sampling chambers of standard size. These relatively small piston chambers (the smaller measures 28.0 cm in length by 2.5 cm in diameter, and the larger 28.0 cm by 3.5 cm) are useful in pollen sampling and stratigraphical work where penetration by a larger sampler is impossible. However, for more satisfactory cores revealing greater stratigraphical details, reducing the risks of contamination, and providing suitable samples from which to obtain material for radiocarbon assay, a larger device was built in Scotland to departmental specifications (see Appendix 3). This larger sampler, called an Abbey Piston Corer, has an overall length of 66.0 cm and an internal diameter of 5 cm. The long chamber enables the collection of fully 50 cm cores with each sampling attempt, after trimming the disturbed ends of the cores, and such large cores both speed up and facilitate stratigraphical investigations.

The treatment of the cores for storage in the laboratory is the same as that described for the samples collected by the Livingstone piston sampler.

3. STRATIGRAPHICAL INVESTIGATIONS

The purpose of these investigations was to obtain standard profiles of the main features of the Lateglacial and early Flandrian vegetational history by pollen analysis. For this purpose infilled basins of small size were selected. This ensures that the deepest sampling point at each particular location is accessible with the limited equipment available, and also avoids the special problems encountered in palynological interpretations based on the sediments of larger basins. The deepest sampling point is usually found at the central part of a basin, and it is this central part that is the desired location for pollen sampling because of the likelihood of uniform and rapid pollen sedimentation (Faegri and Iversen, 1964).

The deepest part of each site usually reveals the fullest and most detailed features of profile development, and this is a crucial factor in the present enquiry where the relative complexity or uniformity of the Lateglacial and early Flandrian periods are under scrutiny. Each basin selected for detailed analysis was therefore sampled at numerous points in order to ensure that the deepest point was obtained, and that this point also contained the fullest representation of stratigraphical variation for that basin. The prevention of further penetration by the coring devices was caused in almost every case by the presence at the base of gravel, pebbles, or coarse sand. Only at one site, Amulree, were fine-grained lake sediments present that were too compact to prevent further penetration of even the narrowest coring device. (Gravel was reached by one core, however, believed to be representative of the deepest part of the basin - see below). It is a basic assumption of this thesis (and all other investigations of this nature) that the earliest accumulation of sediments in any particular basin took place almost immediately after the formation or subsequent exposure of that basin.

Several areas have been surveyed by the author (and other members of the Edinburgh University Geography Department) in the search for suitable sites. The method followed in areas unfamiliar to the author, and in relatively inaccessible areas, was to use aerial photographs in order to locate possible basin sites. In those basins so delimited the major requirements sought for were a sufficient depth of sediment (a sediment depth of, say, less than 3 metres, which included both Lateglacial and Flandrian sediments, would be unsuitable for the objectives in mind owing to the probable shallow nature of the important parts of the profile); the presence of some visible indications that the site contained sediments of the Lateglacial period or at least of the early Flandrian period (indications of the latter could be presumed from the presence at the base of clay or gyttja, a characteristic "transition sediment" between Lateglacial clays and Flandrian peat); and a continuous stratigraphical sequence giving no indications of major interruptions in deposition.

Several problems were encountered which will become apparent from the remaining sections of this chapter. Four separate areas within the southern part of Thompson's study area have been investigated during the search for suitable pollen sites. These areas, covering a sizeable region in the southern Grampians, yielded surprisingly few basin sites that met the above requirements.

(i) The Teith Valley (Fig. 6)

Within the ice-sheet decay deposits to the south-east of Callander (beyond the Callander terminal moraine) are to be found several kettle-hole basins infilled with sediments. The stratigraphy of the sediments was investigated at two locations within these fluvioglacial features. Sediments in excess of 11 m in depth were recorded from an infilled kettle-hole near Cambusbeg farm, about 2.5 km south-east of Callander, and about 1.5 km south-east of the end-moraine (Figs. 6 and 9). The bottom 60 cm of sediments from this basin contained mainly fine grey clay, some of the clay showing evidence of a slight organic content. The expected basal alternation of clay-peat-clay indicating the Lateglacial oscillation was not found. A site with more probable stratigraphical indications of Lateglacial origins was therefore sought.

Near Tynaspirit farm, a further 0.5 km south-eastwards from Cambusbeg, a series of connecting kettle depressions of varying depths occurs amongst large-scale kamiform deposits. The recognisable Lateglacial stratigraphical pattern of clay - organic-rich deposits - clay, was found in the basal deposits of two of these depressions, one of maximum depth 450 cm, and the other of 670 cm. Various pollen profiles are described from the sediments of both these basins.

With the exception of one site, no basins with sediments of comparable depths to those of Cambusbeg and Tynaspirit could be discovered in the Teith Valley within the Callander terminal moraine. There is a definite change of character in the deposits within the Callander end-moraine in comparison to the obvious ice-decay features to the south-east, and this is reflected in the acute shortage of obvious kettles or of other distinct depressions. Fortunately one large infilled basin lies about 1 km inside the end-moraine, a dead-ice hollow within a suite of kame terraces in the vicinity of Mollands farm with deposits in excess of 8.5 m.

(ii) The region around Glen Almond (Fig. 7)

The Loch Lomond Readvance downvalley limit in Glen Almond, according to Thompson, is located in the vicinity of Newton Bridge, where the River Almond turns sharply southwards into the Sma' Glen in its flow towards Crieff. The limit here is not as sharply delimited as in the Teith Valley. No depressions containing sufficient sediments for use in the present investigation could be found in the deposits of the Sma' Glen, and throughout upper Glen Almond, within the readvance limit, again no suitable sites could be found despite intensive search. Within upper Glen Almond, which is over 15 km long from Newton Bridge to the headwaters of the River Almond, are extensive spreads of very distinctive hummocky drift. Significant depths of sediment have not accumulated in the depressions between the large hummocks. Numerous test bores have been made throughout Glen Almond and the Sma' Glen by the author and several members of the Department of Geography at Edinburgh but nowhere were sediments in excess of 2 m depth discovered.

Within the valley of the Girron Burn which connects Glen Almond and the next major valley to the north, Glen Quaich, lies a large infilled lake basin. This depression lies within ice-decay features about 4 km to the north of the proposed downvalley limit of Loch Lomond Readvance ice in Glen Almond. It contains a maximum recorded depth of 12 m of sediments of which the lowermost 320 cm are composed predominantly of clay deposits. Indications of a Lateglacial oscillation are not visually evident from the sediments of this basin, named Amulree.

The search for a suitable Lateglacial site was continued towards the north in the vicinity of Amulree and in Glen Quaich. A systematic inspection of depressions within the kame complex between Amulree and Loch Freuchie in upper Glen Quaich failed to reveal any sediments in excess of about 2 m. Only dark humified peat was found at all of the inspected depressions, with barely 4 or 5 cm of light grey clay at the base. Because of the apparent lack of suitable sites within this region

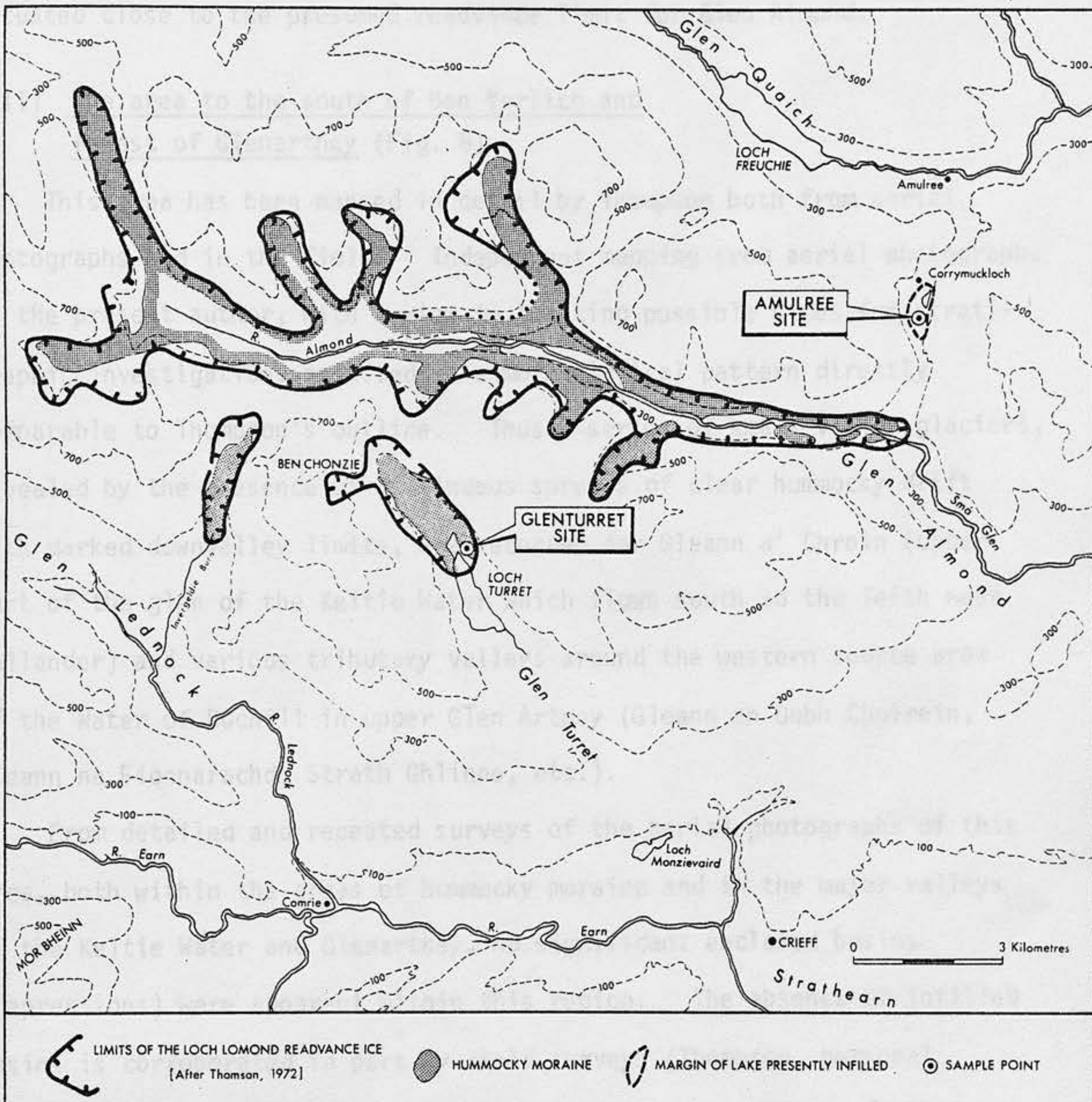


FIGURE 7 Glacial limits in Glen Almond, Glen Turret and the valley of the Invergeldie Burn (after Thompson, 1972) and location of pollen sites. Contours in metres.

it was decided to investigate the deposits of the Amulree basin. In addition, the valley of the Girron Burn occupies a critical position in Thompson's hypothesis, for it is a narrow but exposed through-valley at over 300 m in altitude, enclosed by mountains exceeding 650 m, and it is situated close to the presumed readvance limit for Glen Almond.

(iii) The area to the south of Ben Vorlich and Forest of Glenartney (Fig. 8)

This area has been mapped in detail by Thompson both from aerial photographs and in the field. Independent mapping from aerial photographs by the present author, with a view to locating possible sites for stratigraphic investigation, resulted in a morphological pattern directly comparable to Thompson's outline. Thus a series of small valley glaciers, revealed by the presence of continuous spreads of clear hummocky drift with marked downvalley limits, are recorded for Gleann a' Chroin (upper part of the glen of the Keltie Water which flows south to the Teith near Callander) and various tributary valleys around the western source area of the Water of Ruchill in upper Glen Artney (Gleann an Dubh Choirein, Gleann na Fionnarachd, Strath Ghlinne, etc.).

From detailed and repeated surveys of the aerial photographs of this area, both within the areas of hummocky moraine and in the major valleys of the Keltie Water and Glenartney, no significant enclosed basins (depressions) were apparent within this region. The absence of infilled basins is corroborated in part by field surveys (Thompson, personal communication). Attention was therefore directed to an area farther east, in the environs of Crieff and Comrie.

(iv) Comrie-Crieff region, and the glens to the south of Ben Chonzie (Fig. 7)

In this region the limits of the Loch Lomond Readvance lie in upper Glen Turret and the upper part of the valley of the Invergeldie Burn, or farther to the west in upper Glenartney. Aerial photographic survey of

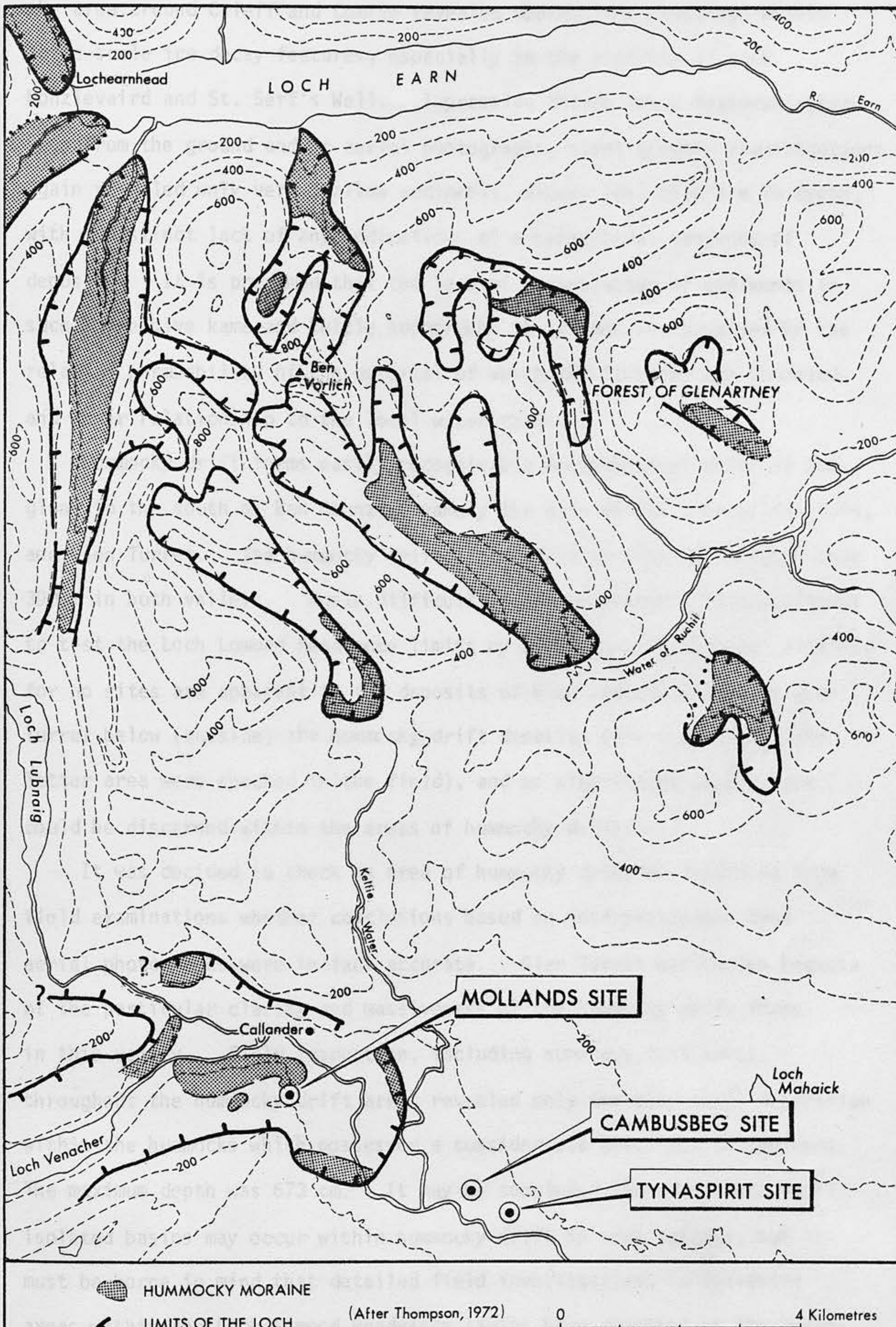


FIGURE 8 Glacial limits in the Teith Valley and the uplands to the south of Loch Earn (after Thompson, 1972) and location of pollen sites. Contours in metres.

the area around Crieff and Comrie revealed depressions (kettles) within large-scale ice decay features, especially in the vicinity of Loch Monzievaird and St. Serf's Well. Impressive though these features appear both from the ground and in aerial photographs, stratigraphic investigations again revealed only very shallow sediments, always less than 3 m in depth, with a distinct lack of any indications of a Lateglacial sequence of deposits. It is presumed that the lack of accumulation of sediments in such impressive kame and kettle topography is in some way governed by the relative permeability of the material of which the features are composed, and their relationship to the local water-table.

Hummocky drift forms easily recognisable morphological units in two glens to the south of Ben Chonzie, namely the glen of the Invergeldie Burn, and Glen Turret. The hummocky drift is confined to altitudes higher than 390 m in both valleys. Again difficulties are encountered in any attempt to test the Loch Lomond Readvance limits by selected palynological studies, for no sites are apparent in the deposits of Glen Lednock and lower Glen Turret below (outside) the hummocky drift deposits (the deposits of the latter area were checked in the field), and no significant depressions could be discerned within the areas of hummocky drift.

It was decided to check an area of hummocky drift to determine from field examinations whether conclusions based on interpretations from aerial photographs were in fact accurate. Glen Turret was chosen because of the particular clarity and massiveness of the hummocky drift forms in this valley. Field inspection, including numerous test bores, throughout the hummocky drift areas revealed only one very small depression within the hummocks which possessed a considerable thickness of sediment. The maximum depth was 673 cm. It may be concluded therefore that small isolated basins may occur within hummocky drift in some valleys, but it must be borne in mind that detailed field investigations in extensive areas within the Loch Lomond Readvance limits have resulted in the determination of only two locations where significant sediment accumulation has occurred, and deposits of early Flandrian age are absent from the Glenturret site (see chapter 7).

The first clear problem thus revealed by the above investigations is the apparent lack of basins possessing the required qualities for this particular kind of enquiry in areas with excellent morphological features where it would be reasonably expected that such basins would exist. A paucity of significant accumulations of sediment is characteristic of areas of hummocky drift, which therefore results in serious difficulties since this feature is taken to be the most characteristic morphological expression of the Loch Lomond Readvance. The lack of suitable basins is also apparent within large areas of ice-sheet decay features even although some well formed kettles are present.

In an area to the east of that studied in this thesis, comprising Glenshee, Glen Prosen, Glen Clova, and Glen Esk (and also including the area around the Pass of Drumochter farther to the north), a comparable investigation into the history of deglaciation has also revealed the marked scarcity of basins possessing significant postglacial sediments within the limits of the Loch Lomond Readvance (M.J.C. Walker, personal communication). Investigations into areas of Loch Lomond Readvance deposits by other members of the Edinburgh University Geography Department also suggest this to be a characteristic feature of areas within the readvance limits, though detailed stratigraphical surveys have not been conducted throughout the relevant areas (J.B. Sissons, K.S.R. Thompson, D. Sutherland, personal communications). It is significant that nearly all the sites investigated within the readvance limits that contain a full representation of Flandrian vegetation developments refer either to relatively large open water upland lochs and lochans (Donner, 1962; Moar, 1969a, b and c; Vasari and Vasari, 1968; Pennington <u>et al</u>., 1972), or to areas where well marked large-scale terminal moraines exist, as at Gartmore (Donner, 1957), Glen Torridon (Lowe, 1970), Callander, and lower Glen Treig (Lowe, unpublished). The absence of suitable sites with early

Flandrian deposits in areas of hummocky moraine is discussed in Appendix 4.

It was decided to investigate in detail the five major basins discovered by these preliminary studies - viz. Tynaspirit, Cambusbeg, Mollands, Amulree, and Glenturret - rather than to continue the search for basins possessing some presupposed ideal qualities. The five sites are located close to each other and it was therefore felt that there was a fair degree of probability of regional continuity in major vegetational developments, thus permitting some provisional correlations. Three of the sites are also located in the most crucial area of Thompson's study, the Teith Valley.

4. DETAILED STRATIGRAPHIC ANALYSIS

A. Tynaspirit 1 (Nat. Grid Ref. NN/667 047)

Near Tynaspirit Farm, about 2.5 km south-east of the Callander terminal moraine, is a large peat-filled depression in fluvioglacial deposits (kames and eskers). The present-day bog surface is about 450 m long and averages about 100 m in width. Boring revealed that a series of small basins is covered by a general spread of Flandrian peat. The altitude of the bog surface is at about 60 m O.D., and a small stream crosses the bog in a north to south direction whereafter it flows into the River Teith (Fig. 9).

This large peat-filled depression was sampled at numerous locations to establish the nature of the sub-surface morphology. A series of small depressions was discovered, and initially, the deepest sampling point in the deepest basin was chosen for sampling for subsequent pollen analysis. The generalised stratigraphy can be summarised as follows:-

Lithostratigraphic unit (see Figs. 15 and 16)	cm from surface	sediment
	0 - 70	Present-day root zone and active growth layer.
	70 - 390	Light brown soft wet peat with numerous remains of root material.
	390 - 418	Darker brown humified peat with wood fragments.
	418 - 430	Dark brown humified peat
L.u. 7	430 - 480	Blackish-brown peat with occasional *Sphagnum* remains and less occasional small decomposed wood fragments.
	480 - 562	Blackish-brown humified peat - few macrofossil remains
L.u. 6	562 - 568	Brown peaty-gyttja.
L.u. 5	568 - 600	Light grey, soft clay.
L.u. 4	600 - 618	Brown peaty-gyttja.
L.u. 3	618 - 621	Light brown gyttja.
L.u. 2	621 - 650	Grey clay, compact, getting more compact with depth with sand particles towards the base.
L.u. 1	650 - 665	Sandy-clay material, getting sandier with depth, and with occasional gravel inclusions towards base.
	665 cm :	GRAVEL - further penetration of sediments not possible with Hiller equipment

The source of most of the clay found at the base of the sediments probably lay outside the basin itself, for the material surrounding the basin is composed of coarse sand and gravel with an extremely limited clay component (Thompson, 1972). Yet the clay layers in the basins examined form definite layers up to 30 cm in thickness. It is presumed that the clay material has been provided by the small stream which drains an area covered in clay-till material towards the north. It seems likely that the clay was supplied to the stream during a time of increased solifluction.

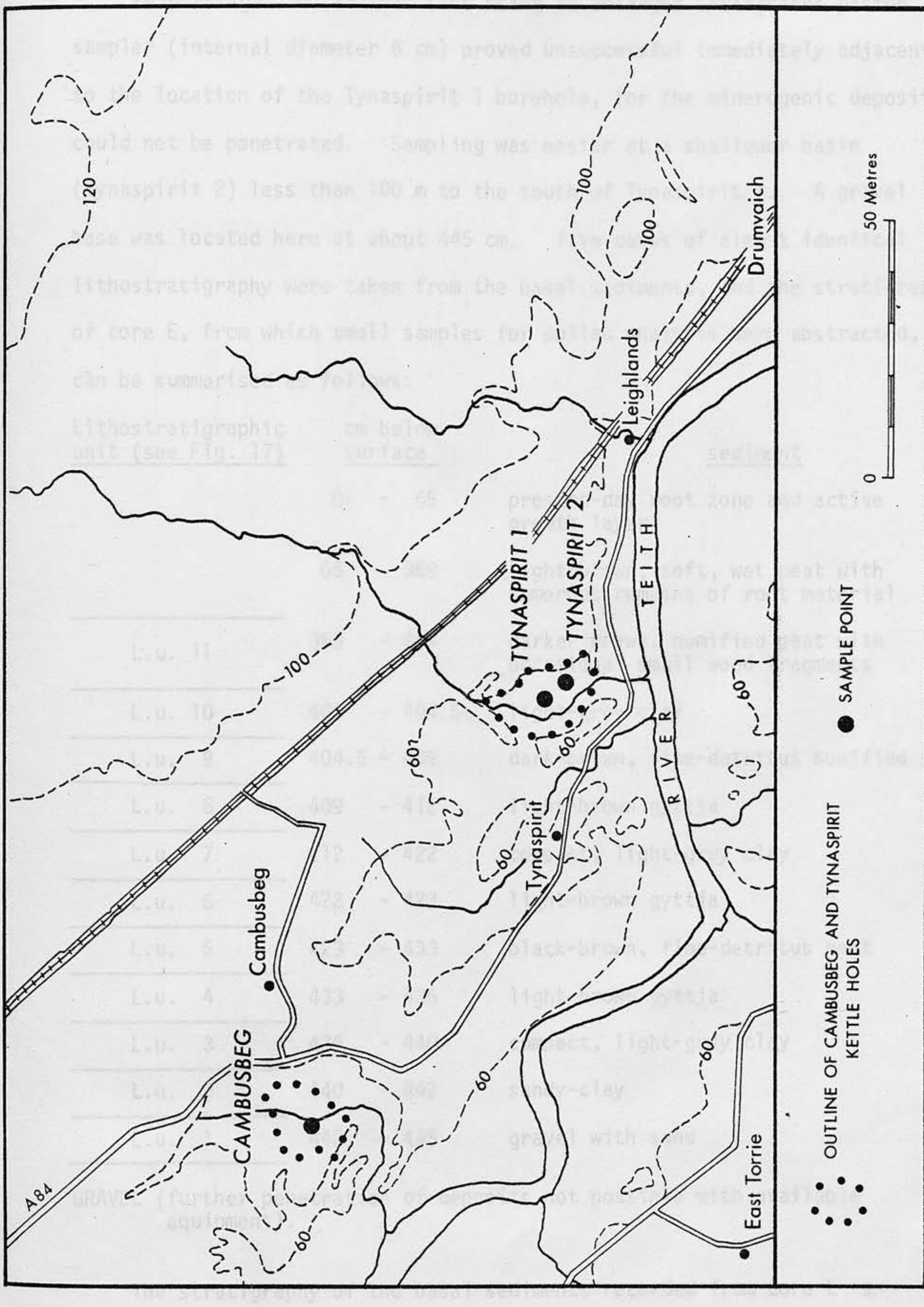


FIGURE 9 Detailed location of Tynaspirit and Cambusbeg pollen sites. Contours in metres.

B. Tynaspirit 2 (NN/ 667 047)

Reinvestigation at this site using an enlarged Livingstone piston sampler (internal diameter 6 cm) proved unsuccessful immediately adjacent to the location of the Tynaspirit 1 borehole, for the minerogenic deposits could not be penetrated. Sampling was easier at a shallower basin (Tynaspirit 2) less than 100 m to the south of Tynaspirit 1. A gravel base was located here at about 445 cm. Five cores of almost identical lithostratigraphy were taken from the basal sediments, and the stratigraphy of core E, from which small samples for pollen analysis were abstracted, can be summarised as follows:

Lithostratigraphic unit (see Fig. 17)	cm below surface	sediment
	0 - 65	present-day root zone and active growth layer
	65 - 369	light-brown, soft, wet peat with numerous remains of root material
L.u. 11	369 - 404	darker brown, humified peat with occasional small wood fragments
L.u. 10	404 - 404.5	light-grey clay
L.u. 9	404.5 - 409	dark-brown, fine-detritus humified peat
L.u. 8	409 - 412	light-brown gyttja
L.u. 7	412 - 422	compact, light-grey clay
L.u. 6	422 - 423	light-brown gyttja
L.u. 5	423 - 433	black-brown, fine-detritus peat
L.u. 4	433 - 436	light-brown gyttja
L.u. 3	436 - 440	compact, light-grey clay
L.u. 2	440 - 442	sandy-clay
L.u. 1	442 - 445	gravel with sand

GRAVEL (further penetration of deposits not possible with available equipment).

The stratigraphy of the basal sediments recorded from core E is compared with those of cores A - D in Fig. 10. The maximum horizontal

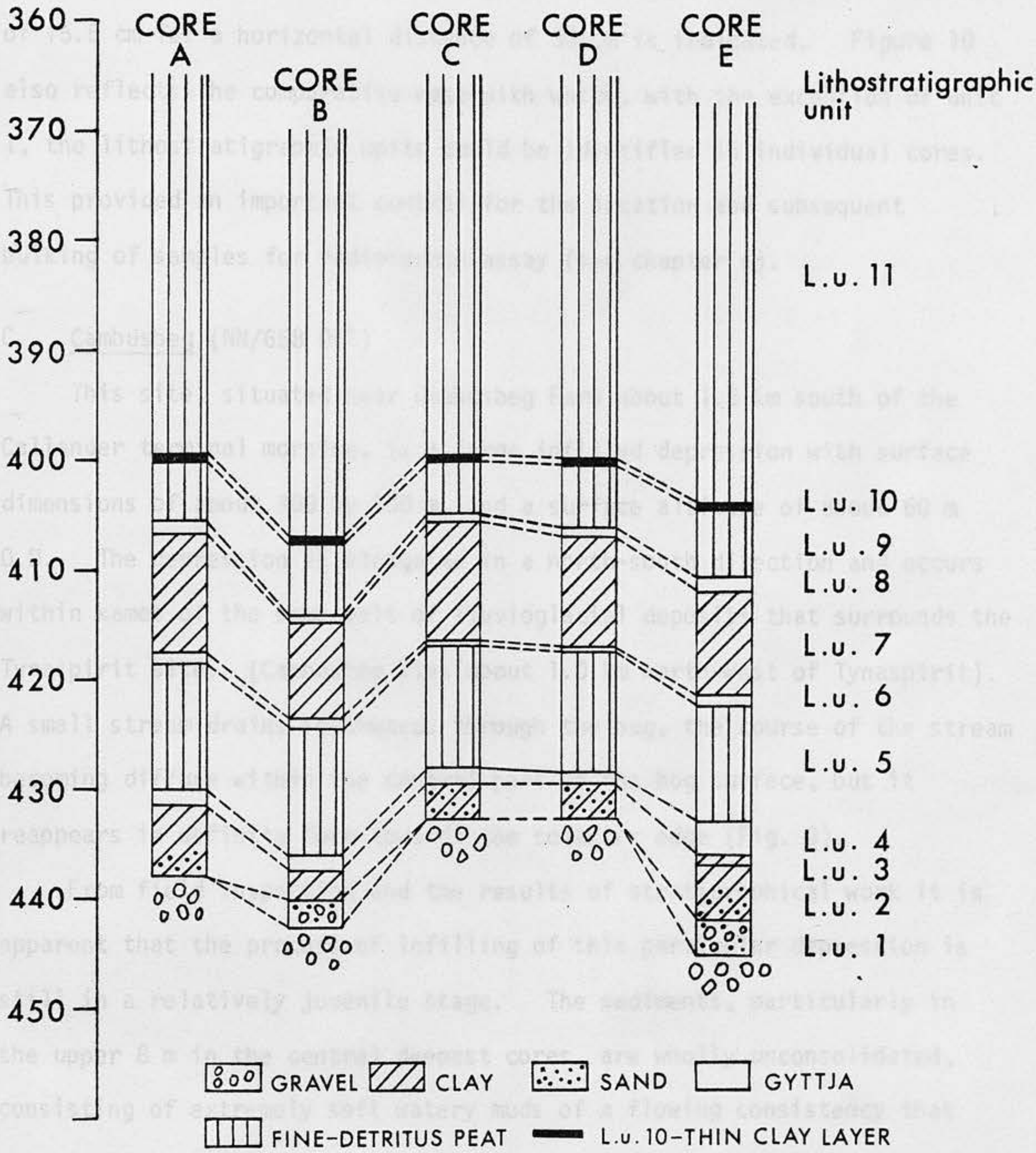


FIGURE 10 Lithostratigraphy of basal sediments at Tynaspirit 2. Scale at left hand edge represents depth in cm below surface of the mire.

distance between any two adjacent cores was 30 cm, and the maximum horizontal distance between any two cores was 60 cm. This figure reveals undulations in the boundaries between lithostratigraphic units 1-11 over short horizontal distances. The maximum variation in depth between any two cores for an organic horizon was that for the lithostratigraphic 3/4 boundary between cores B and C. A vertical difference of 15.5 cm for a horizontal distance of 30 cm is indicated. Figure 10 also reflects the comparative ease with which, with the exception of unit 1, the lithostratigraphic units could be identified in individual cores. This provided an important control for the location and subsequent bulking of samples for radiocarbon assay (see chapter 4).

C. Cambusbeg (NN/658 051)

This site, situated near Cambusbeg Farm about 1.5 km south of the Callander terminal moraine, is a large infilled depression with surface dimensions of about 300 by 100 m, and a surface altitude of about 60 m O.D. The depression is elongated in a north-south direction and occurs within kames of the same belt of fluvioglacial deposits that surrounds the Tynaspirit site. (Cambusbeg lies about 1.0 km north-west of Tynaspirit). A small stream drains southwards through the bog, the course of the stream becoming diffuse within the central part of the bog surface, but it reappears in definite form towards the southern edge (Fig. 9).

From field inspection and the results of stratigraphical work it is apparent that the process of infilling of this particular depression is still in a relatively juvenile stage. The sediments, particularly in the upper 8 m in the central deepest cores, are wholly unconsolidated, consisting of extremely soft watery muds of a flowing consistency that rendered sampling at this site exceedingly difficult. The surface consists of a 'floating mat' of decomposed and living vegetation, up to 1.5 m thick, that quakes easily under pressure.

Boring shows that the basin is an elongated depression with the deepest part along the central north-south axis. The edge of the depression is quite irregular, representing the lateral slopes of kamiform deposits, but on the whole the basin sides are relatively steep in inclination for the upper 7 m, below which there is usually a more gentle inclination towards the centre.

The detailed stratigraphy for the deepest core obtained, from which samples for pollen analysis were abstracted, is given below. The clay layers found at the base of the sediments represented only 50 cm at most in the cores sampled, and they were found only in the narrow deep central portion of the basin, generally in those parts deeper than 7 m. It is evident from the stratigraphic data that there is not a clear lithological representation of the Lateglacial sequence in the deposits at Cambusbeg: in fact there is a very complicated alternation of lithology. Samples for pollen analysis were taken from the sediments between the base of the depression and that point at which the Flandrian muds became too inconsistent for satisfactory sampling.

Lithostratigraphic unit (see Figs. 18 and 19	cm from surface	sediment
	0 - 148	Surface 'mat' of decomposed and living vegetation, mainly roots.
	148 - 870	Extremely soft brown mud of a flowing consistency; no samples taken.
L.u 9 to L.u.15	870 - 1022.5	Dark brown/black organic-rich mud, extremely decomposed with few recognisable macrofossil remains. This material is tentatively termed "dy" from the descriptions in Faegri and Iversen, 1964. Three thin sand layers occur within these organic deposits.
L.u.8	1022.5 - 1025	Yellowish-brown silty clay.
L.u.7	1025 - 1030	dy
L.u.6	1030 - 1035	Greyish, silty, organic clay - basically dy material with clay-silt inclusion.
L.u.5	1035 - 1094	dy

Lithostratigraph unit (see Figs. 18 and 19)	cm from surface	sediment
L.u.4	1094 - 1099	Dark, greenish-brown, organic mud with slight clay inclusion. Material still very soft and decomposed, but gradually becoming slightly stiffer with depth.
L.u.3	1099 - 1135.5	Dark, grey-brown, organic-rich mud with clay and silt components - this material is more compact and lighter in colour than the dy material described above.
L.u.2	1135.5 - 1142	Light-grey, silty clay.
L.u.1	1142 cms : GRAVEL?	- further penetration impossible with the Hiller sampling equipment

D. Mollands (NN/627 067): samples collected by Hiller

Near Mollands Farm, which lies about 1.5 km due south of Callander station, lies a large infilled depression enclosed by a suite of outwash terraces. The kame terraces are related by Thompson to the decay of the ice that produced the Callander terminal moraine that lies about 1.5 km south-east of Mollands. The basin is about 500 m in length and 120 m broad, and is elongated in a west-south-west to east-north-east direction. It has a broad almost flat floor that slopes downwards gently towards the south-west, and possesses steep sides representing the edges of various outwash terraces. A small stream flows along the long axis but towards the southern edge of the present-day bog surface, the altitude of which lies at about 75.0-80.0 m O.D. (Fig. 11).

According to Thompson this hollow was occupied by ice during the deposition of part of the outwash terrace sequence. Ice probably vacated the hollow whilst the Teith Valley glacier was still present in the Callander area, though the glacier snout was by this time much reduced in dimensions. Two small subglacial meltwater channels enter the Mollands depression at its western edge, so that one might expect from this situation that in the time immediately following deglaciation extremely active conditions would be reflected by thick accumulations of inorganic

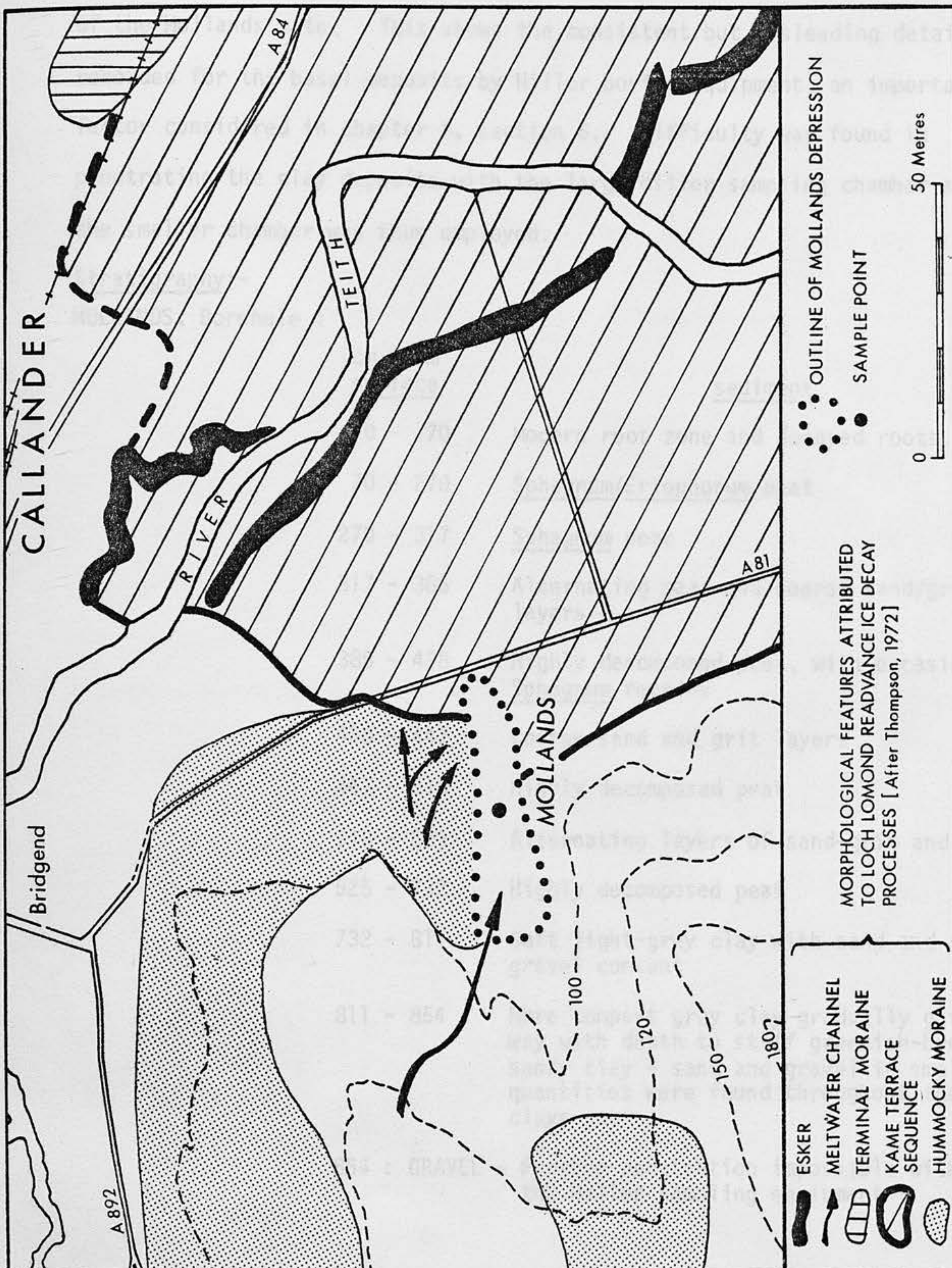


FIGURE 11 Detailed location of Mollands pollen site.
Contours in metres.

sediments at this locality.

The detailed stratigraphy is presented here for three core records that are typical for the deposits as a whole in the broad central part of the Mollands site. This shows the consistent but misleading details recorded for the basal deposits by Hiller boring equipment, an important factor considered in chapter 5, section 6. Difficulty was found in penetrating the clay deposits with the large Hiller sampling chamber and the smaller chamber was thus employed.

Stratigraphy:-

MOLLANDS, Borehole 1

cm from surface	sediment
0 - 70	Modern root zone and decayed roots.
70 - 270	*Sphagnum*/*Eriophorum* peat
270 - 317	*Sphagnum* peat
317 - 385	Alternating peat and coarse sand/grit layers
385 - 438	Highly decomposed peat, with occasional *Sphagnum* remains
438 - 447	Coarse sand and grit layers
447 - 518	Highly decomposed peat
518 - 525	Alternating layers of sand-grit and peat
525 - 732	Highly decomposed peat
732 - 811	Soft light-grey clay with sand and some gravel content
811 - 854	More compact grey clay gradually giving way with depth to stiff greenish-brown sandy clay - sand and gravel in small quantities were found throughout the clays
854 : GRAVEL	- Further penetration impossible with the Hiller sampling equipment

MOLLANDS, Borehole 2

cm from surface	sediment
0 - 66	Modern root zone and decayed roots of limited decomposition
66 - 280	*Sphagnum*/*Eriophorum* peat
280 - 397	*Sphagnum* peat
397 - 440	Highly decomposed peat
440 - 449	Highly decomposed peat with thin bands of fine sand
449 - 522	Highly decomposed peat
522 - 528	Alternating layers of sand/grit and peat
528 - 726	Highly decomposed peat
726 - 811	Soft light grey clay, with sand and some gravel particles throughout
811 - 852	Transition downwards from light grey clay to stiff greenish-brown sandy clay, with sand and some gravel particles throughout
852 ;	GRAVEL - Impenetrable

MOLLANDS, Borehole 3

Lithostratigraphic unit (see Fig. 24)	cm from surface	sediment
	0 - 40	Modern root zone and decayed roots of limited decomposition
L.u.7	40 - 50	*Sphagnum* peat
L.u.6	50 - 95	dry, humified peat
L.u.5	95 - 299	fine-detritus peat, with abundant *Sphagnum* remains
L.u.4	299 - 370	fine-detritus peat with *Sphagnum* remains and decomposed wood fragments
L.u.3	370 - 705	highly humified peat
L.u.2	705 - 716	light-brown gyttja
L.u.1	716 - 796	soft, light-grey clay
	796 - 843	More compact grey clay gradually giving way to sandy-clay - occasional thin layers of sand and gravel
	843 - 858	coarse, greenish-brown sand
	858 ;	GRAVEL - impenetrable

The Mollands site was chosen as the location for a detailed Flandrian pollen diagram that could be used as a type-site to which the other partial pollen diagrams included in this investigation could be related, and which could be used for comparison with published regional postglacial pollen diagrams. This decision was governed by several factors. Firstly, the compact nature of the sediments (especially compared with those at Cambusbeg) allows a certain degree of confidence in the sampling technique with the Hiller equipment, for in every case complete continuous cores were obtained that showed no signs of disturbance. Secondly, this is the longest postglacial stratigraphical column obtained for the Callander district and thus, it was assumed, this site offered the possibility of greater historical detail in subsequent analyses. No signs of interruption in the sequence of deposits was evident apart from the disturbed zone at the base of the modern root zone.

Samples for pollen analysis of the organic deposits were collected from Mollands Borehole 3, since this was the deepest point obtained when sampling with the Hiller, and also because this borehole was located at a central point in the Mollands depression which showed no signs of interruption in the accumulation of peat deposits by the occasional minerogenic layers evident in boreholes 1 and 2. These layers of coarse sand with occasional grit, ranging in thickness from a centimetre or two to between 10 and 20 cm, are assumed to be related to past courses or to flooding of the small stream that presently traverses the surface of the deposits. Both the frequency and the thickness of these minerogenic bands increase with proximity to the present stream course (of the three boreholes referred to above borehole 1 is nearest to the present stream course and borehole 3 the most distant). The danger of partial destruction of the sedimentary sequence by stream action was avoided by choosing borehole 3 for detailed analysis.

Using the smaller Hiller chamber samples were collected for pollen analysis of the minerogenic deposits from a fourth borehole located close to borehole 3. The stratigraphy recorded from borehole 4 was as follows:

Lithostratigraphic unit (Fig. 23)	cm below surface	sediment
3	705 - 726	highly humified peat
2	726 - 839	soft, light-grey clay, becoming stiffer with depth and also becoming more silty and sandy
1	839 - 853	coarse sand (greenish) and gravel
	853 : GRAVEL - impenetrable	

E. MOLLANDS (NN/627 067): samples collected by Abbey piston corer

The basal sediments at Mollands were reinvestigated using an Abbey piston corer of internal diameter 5 cm. A total of 11 cores were collected, and downward penetration was eventually halted by compact coarse sands at the base. These sands also proved impenetrable when using the small chamber (internal diameter 2.5 cm) of the Dachnowski piston sampler (see core 12 below). With the exception of core 6, where the sediments were extremely distorted, the stratigraphy recorded in each core can be summarised as follows:

Core. No.	cm below surface	sediment
1	654 - 696	black, highly humified peat
	696 - 705	brown peaty-gyttja
	705 - 708	brown gyttja
2	655 - 703	black, highly humified peat
	703 - 708	greenish-brown gyttja
3	655 - 687	black, highly humified peat
	687 - 690	layer of small wood fragments
	690 - 696	black, highly humified peat
	696 - 701	greenish clay-gyttja
	701 - 709	laminated clay and silty-clay; mostly blue-grey in colour, but coarser layers with a pink tinge
4	658 - 704	black, highly humified peat
5	657 - 703	black, highly humified peat
	703 - 706	greenish-brown gyttja

Core No	cm below surface	sediment
7	682 - 701	black, highly humified peat
	701 - 707	brown peaty-gyttja
	707 - 708	greenish-brown gyttja
	708 - 708.5	brown peaty-gyttja
	708.5 - 716	laminated gyttja and peat; extremely thin organic bands, increasing in thickness upwards
	716 - 725	laminated green gyttja and grey clay; extremely thin layers, clay layers decreasing in thickness upwards
	725 - 732	light-grey clay, finely laminated with silty-clay
8	725 - 745	soft, light-grey clay, finely laminated with silty-clay
	745 - 752	gravel; average diameter of particles, 5.0 - 6.0 mm; largest clast with diameter 20 mm.
	752 - 755	grey clay (compact)
	755 - 759	fine sand
	759 - 778	very compact grey clay; clearly laminated, but laminations thin; some layers of fine sand, which have a purplish-pink tinge.
9	729 - 750	very compact laminated clay
	750 - 760	gravel and sand, separated vertically (see Fig. 12)
	760 - 763	compact grey clay
	763 - 766	fine sand
	766 - 782	very compact laminated grey clay and fine sand
10	765 - 769	laminated clay and fine sand
	769 - 773	compact grey clay
	773 - 777	fine sand
	777 - 787	grey clay
	787 - 813	sand, getting coarser towards base.

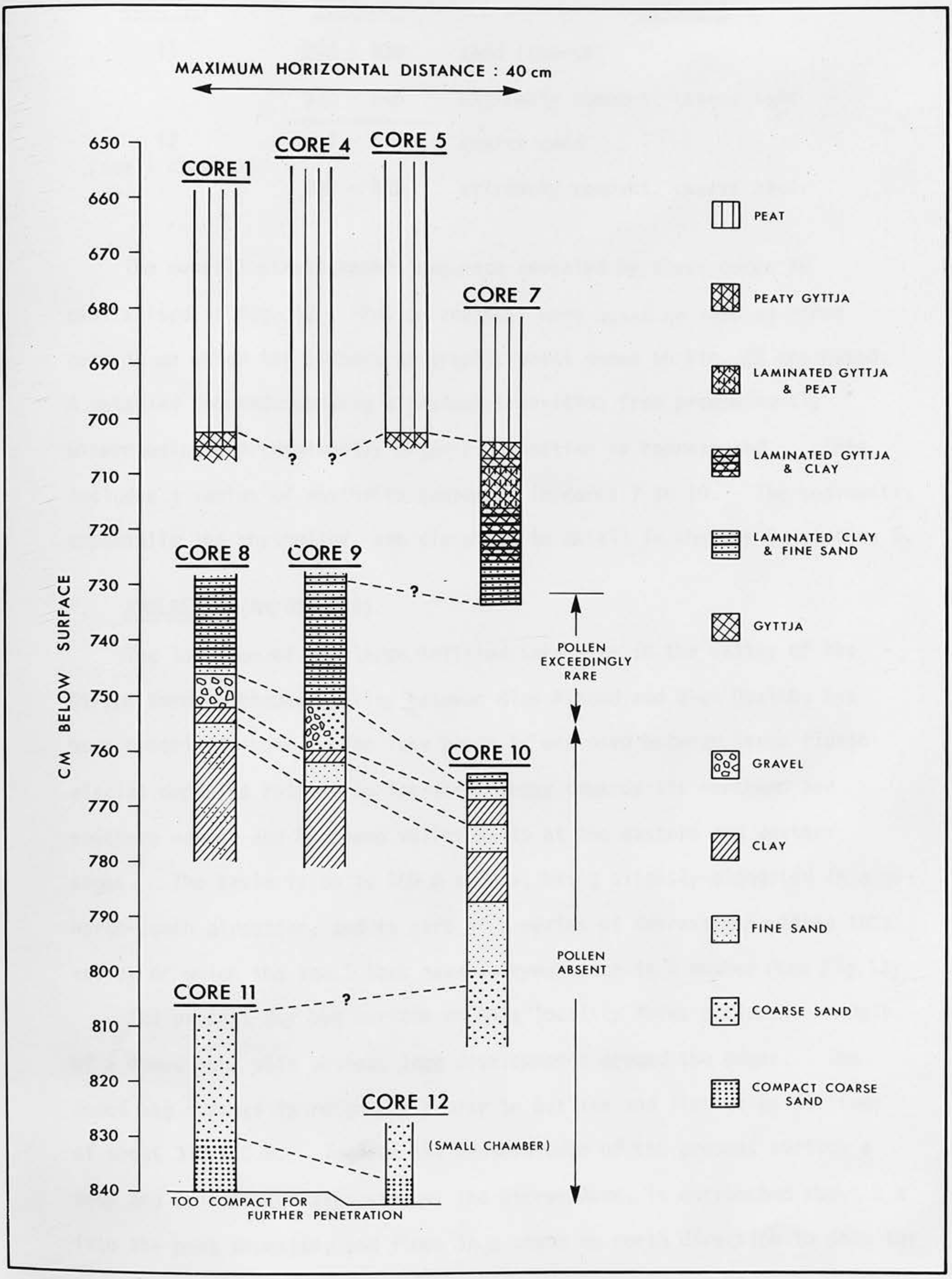


FIGURE 12 Lithostratigraphy of basal sediments at Mollands

Core No.	cm below surface	sediment
11	808 - 830	sand (coarse)
	830 - 840	extremely compact, coarse sand
12 (small chamber)	827 - 836	coarse sand
	836 - 842	extremely compact, coarse sand.

The overall stratigraphic sequence revealed by these cores is generalised in Fig. 12. Pollen analyses were based on samples from core 7, on which the lithostratigraphic units shown in Fig. 25 are based. A detailed sequence showing a gradual transition from predominantly minerogenic to predominantly organic deposition is represented. This includes a series of rhythmite sediments in cores 7 to 10. The sediments, especially the rhythmites, are discussed in detail in chapter 5, section 5.

F. <u>AMULREE 1</u> (NN/895 338)

The location of the large infilled lake site in the valley of the Girron Burn, a through valley between Glen Almond and Glen Quaich, has been described above. The lake basin is enclosed between large fluvio-glacial deposits related to ice-sheet decay towards its northern and southern edges, and by steep valley walls at the eastern and western edges. The basin is up to 500 m across, being slightly elongated in a north-south direction, and is part of a series of depressions within this valley of which the small loch near Corrymuckloch is a member (see Fig.13).

The present-day bog surface at this locality forms a classic example of a domed bog, with obvious lagg developments around the edges. The domed bog surface is roughly circular in outline and lies at an altitude of about 300 m O.D. Towards the eastern edge of the present surface a deep and relatively large stream, the Girron Burn, is entrenched about 2 m into the peat deposits, and flows in a south to north direction to join the River Braan near Amulree.

The recorded sediments for the deepest part of the basin (allowing

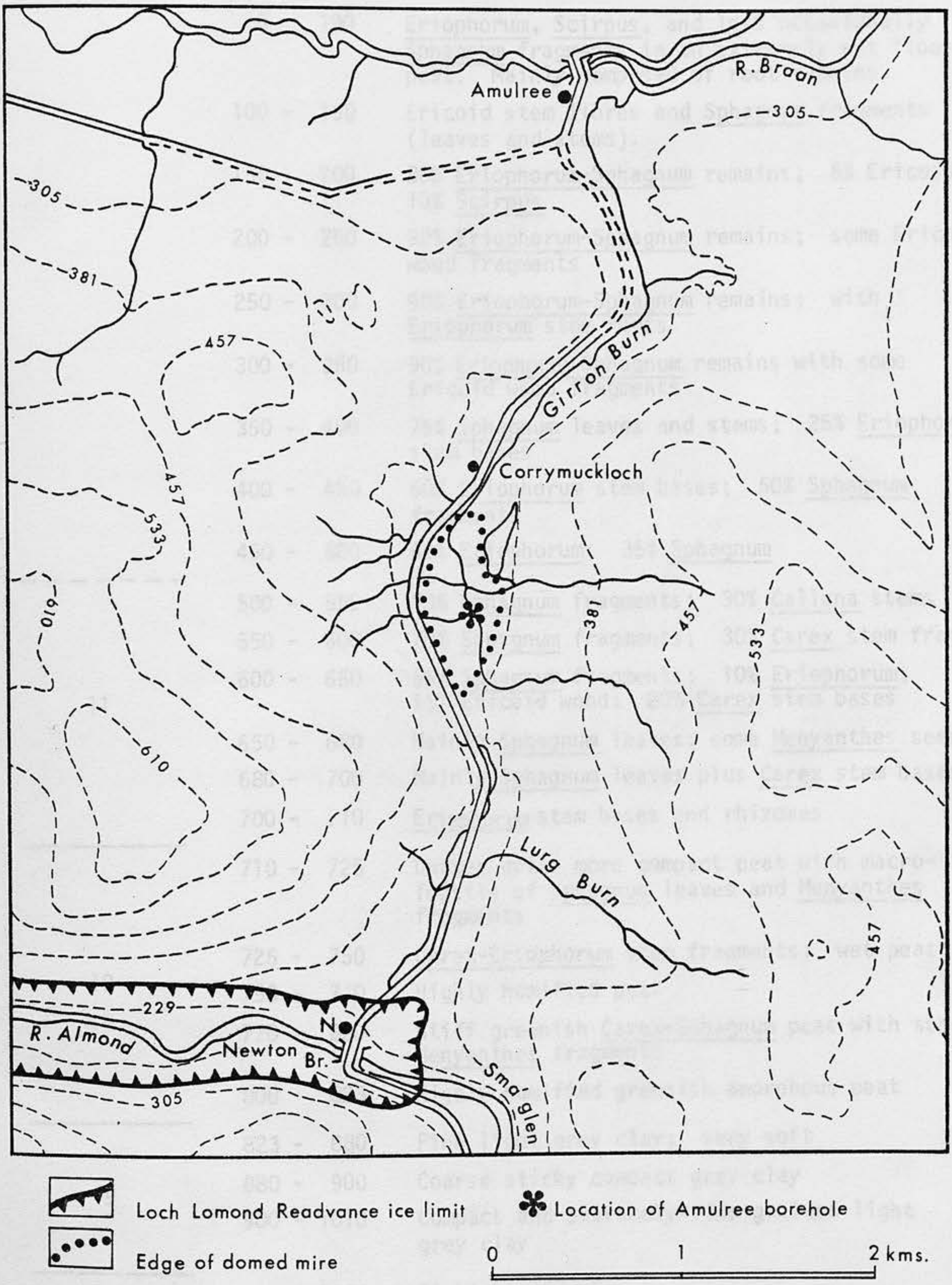


FIGURE 13 Detailed location of Amulree pollen site.
N = Newton. Contours in metres.

for the raised central part of the surface) are as follows:-

Lithostratigraphic unit (Figs.20 & 21)	cm below surface	sediment
	0 - 100	Eriophorum, Scirpus, and less occasionally Sphagnum fragments in an extremely wet "loose" peat. Mainly composed of root remains.
	100 - 150	Ericoid stem fibres and Sphagnum fragments (leaves and stems).
	150 - 200	80% Eriophorum-Sphagnum remains; 5% Ericoid; 10% Scirpus
	200 - 250	90% Eriophorum-Sphagnum remains; some Ericoid wood fragments
	250 - 300	90% Eriophorum-Sphagnum remains; with Eriophorum stem roots
	300 - 350	90% Eriophorum-Sphagnum remains with some Ericoid wood fragments
	350 - 400	75% Sphagnum leaves and stems; 25% Eriophorum stem bases
	400 - 450	50% Eriophorum stem bases; 50% Sphagnum fragments
	450 - 500	65% Eriophorum; 35% Sphagnum
	500 - 550	70% Sphagnum fragments; 30% Calluna stems
	550 - 600	70% Sphagnum fragments; 30% Carex stem fragments
11	600 - 650	55% Sphagnum fragments; 10% Eriophorum; 15% Ericoid wood; 20% Carex stem bases
	650 - 680	Mainly Sphagnum leaves; some Menyanthes seeds
	680 - 700	Mainly Sphagnum leaves plus Carex stem bases
	700 - 710	Eriophorum stem bases and rhizomes
	710 - 725	Darker drier more compact peat with macrofossils of Sphagnum leaves and Menyanthes fragments
	725 - 750	Carex-Eriophorum stem fragments; wet peat
10	750 - 770	Highly humified peat
	770 - 800	Stiff greenish Carex-Sphagnum peat with some Menyanthes fragments
	800 - 823	Highly humified greenish amorphous peat
	823 - 880	Fine light grey clay; very soft
9	880 - 900	Coarse sticky compact grey clay
	900 - 1010	Compact and extremely fine-grained light grey clay
8	1010 - 1026	Pinkish-grey clay
7	1026 - 1054	Grey clay with occasional pinkish tinges throughout; pinkish colour faint and diffuse

Lithostratigraphic unit (Figs. 20 & 21)	cm below surface	sediment
6	1054 - 1082	Light grey clay
5	1082 - 1103	Grey clay with slight pinkish tinge
4	1103 - 1134	Very sticky light grey clay
3	1134 - 1150	Compact clay with strong pink colouration - mottles of very pink clay throughout a background of generally pink clay
2	1150 - 1170	Grey compact clay with slight pink hue
1	1170 - 1200	Compact clay becoming more and more coarse with depth, and exhibiting stronger pink colour with depth
	1200 cm : GRAVEL	- further penetration impossible with available coring equipment

The macrofossil material was identified by Dr. W.W. Newey of the University of Edinburgh. The stratigraphy reveals a complex pattern of peat growth which, in view of the intricate variation characteristic of peat bog growth, is not interpreted in detail here (Bartley, 1960; Stewart and Durno, 1969; Walker, 1970).

A difficulty encountered at Amulree was that the basal clays were locally extremely compact and thus difficult to penetrate. Consequently a full transect of the morphology of the basin was not achieved. A small lateral basin was found to exist at the western edge of the bog. A maximum depth of 7 m was recorded here in a basin of about 70 m width. The deposits shallowed to about 6 m depth revealing a slight "lip" in the basin floor before it plunged quickly to the main depression towards the middle of the valley. Within the small lateral basin no basal clays were found, and a gravel base was established.

Within the main basin penetration to a gravel base was possible at only a few localities. Penetration to base was impeded throughout much of the basin by a very stiff clay. It is thought that those points where penetration to base was possible may in fact be the deeper parts of the basin and contain the thicker sequences of clay deposits, for at these points the top of the clay deposits and the transition from grey to pink clay were recorded at greater depths than the corresponding horizons in cores where penetration to base was prevented.

Thus the indications are that at those points where penetration was impossible with even the small Hiller sampler the basal clay deposits are much shallower than at these localities where further penetration was achieved, and this may in some way account for the marked increase in compaction of the clays at these points. The "deeper" stratigraphical columns were recorded for the eastern half of the Amulree depression, suggesting an asymmetrical base, and the deepest recorded point lies less than 80 m to the west of the present course of the Girron Burn. The typical Lateglacial lithostratigraphic sequence was not discovered in the basal sediments at Amulree, despite a thorough survey of the basin.

G. <u>AMULREE 2</u> (NN/895 338)

The basal sediments at Amulree were reinvestigated using an Abbey piston corer. Eight cores of 5 cm diameter were collected, providing a continuous stratigraphic record between 865 and 1072 cm below surface. The combined records of cores 18, 23, 24 and 25 indicate the sequence of lithostratigraphic units shown in Fig. 22. It was impossible to penetrate deeper than 1072 cm owing to the large sampling chamber of the Abbey corer. Attempts to use the smaller Dachnowski chambers (2.5 and 3.5 cm in diameter) to sample lower levels also failed. The sediments recorded in each core were as follows:-

Core No.	cm below surface	sediment
18	865 - 888	dry, fine-detritus peat (black)
	888 - 923	compact grey clay
19	847 - 885	dry, fine-detritus peat (black)
	885 - 902	compact grey clay
20	865 - 899	dry, fine-detritus peat (black-brown)
	899 - 910	compact grey clay
21	845 - 880	dry, fine-detritus peat (black)
	880 - 904	compact grey clay
22	869 - 899	dry, fine-detritus peat (black)
	899 - 907	compact grey clay
23	918 - 924	compact grey clay
	924 - 955	soft, pale-grey clay
	955 - 970	firm (very compact) grey clay
24	965 - 1015	firm grey clay
	1015 - 1025	laminated, firm grey clay: laminations extremely thin and faint, revealed by a slight colour change only
25	1020 - 1030	laminated firm grey clay (as in core 24) with slight pink colouration to lower clay laminations
	1030 - 1044	grey clay, poorly laminated, with pink colouration
	1044 - 1072	clearly laminated clay, alternating bands of grey and pink clay
	1072 :	clay too stiff for further penetration

Because of the compact nature of the clays the laminations between 1015 and 1072 cm remained relatively undisturbed and well preserved until later examination in the laboratory. These are discussed in detail in chapter 5, section 5.

H. GLENTURRET (NN/802 293)

At the head of Glenturret, up-valley from the northern shore of the present dammed Loch Turret, a sediment-filled depression was found within well-formed hummocky moraine at the eastern side of the glen. This depression is completely encircled by morainic mounds and there is no evidence for any exit that may have prevented the accumulation of water and of sediments in the past. No present-day streams enter the basin for valley-side drainage is diverted down-valley by the coarse morainic material. The site lies at about 360 m O.D.

The basin is elongated in an east-west direction, and is 57 m in length and 31 m broad. The deepest part of the basin occurs close to its western edge (towards the centre of the valley), its asymmetrical form revealed by a gradual inclination in the basin floor towards the east. The large Hiller borer was used for stratigraphic investigations, and the stratigraphy for the deepest point was as follows:

Lithostratigraphic unit (Fig. 26)	cm below surface	sediment
	0 - 75	Modern root zone, recent fibrous peat, and a little decomposed root material
5	75 - 322	Dark humified peat with abundant macro-fossil remains
4	322 - 419	Dry fibrous peat, light orange-brown in colour, with abundant fibrous roots and *Sphagnum* remains
3	419 - 590	Dark brown humified peat, with fibrous root remains, and fragments of wood including some birch
2	590 - 656	Dark humified peat, with slight clay content towards base
1	656 - 673	Light grey clay and coarse gravel - very wet and loose - not sampled
	673 cm : Impenetrable.	

CHAPTER 3

Techniques in pollen analysis and zonation of the pollen diagrams

1. TECHNIQUES IN POLLEN ANALYSIS

As the pollen diagram is strictly an accurate record of the type and number of pollen grains determined by an individual investigator, and classified by him to form the basic data from which the diagram is resolved, it is imperative to know whether, and to what extent, subjective controls have been applied prior to the analysis of the data. The diagram is the culmination of all the technical processes employed in this investigation, and it forms the foundation of qualitative interpretations of the historical development of various environmental factors.

Further, those fossil pollen grains recovered from a sediment are in themselves a distillation of the total number of pollen liberated at any particular time. This distillation process is determined by a complex number of variables that affect pollen liberation, dispersal, deposition and preservation.

> "One must not forget for one moment that the pollen diagram represents nothing but the parts of the pollen rain that have been recovered after fossilization. The object of the diagram is to give a record of the vegetation of the locality in question. The pollen diagram has no direct bearing on any other factor, neither on climate, nor soil, nor exposition, nor on anything else. The first step is to translate the pollen diagram into terms of vegetation and it is only then that an attempt may be made to find the reasons for the vegetational changes observed."
>
> Faegri and Iversen, 1964, p.99

Before presenting the diagrams and attempting to interpret the basic data, it is necessary to give an account of the handling of the fossil material at all stages of its preparation in order that important statements and conclusions can be gauged against the background experience of the investigator. A generalised account of the preparatory techniques used in the palynological investigations of this thesis is now presented.

(a) Chemical preparations of samples

For the majority of samples prepared for pollen counting the standard chemical preparation procedure was as follows:-

(i) For deflocculation and the removal of "humic acids" samples were boiled in 10% KOH or 10% NaOH. The suitability of each of these alkalis for this process was found to vary in both peat and clay samples. In the majority of cases 10% KOH was used, but when deflocculation was found to be very slow or obviously incomplete then the use of 10% NaOH as an alternative was often found to be more effective.

(ii) Sieving, decanting, or differential centrifugation were occasionally used for the removal of large siliceous particles, but for the removal of siliceous components of clay and silt size the samples were treated with 50%-60% hydrofluoric acid. The samples were boiled in HF for 3 to 5 minutes in polythene test-tubes, having been firstly treated with cold dilute HCl. After the HF treatment the samples were washed in warm dilute HCl before being washed with deionised water.

(iii) For the acid hydrolysis of cellulose (acetolysis) the samples were boiled for 30 minutes in test-tubes containing concentrated H_2SO_4 and glacial acetic acid (proportions 1/10).

(iv) After repeated washings in deionised water, prepared samples were mounted in glycerine jelly stained with safranine aqueous.

For the majority of prepared samples a laboratory programme involving both acetolysis and HF treatment was found to be unnecessary. Peat and gyttja samples were not treated with HF, and predominantly clay samples were not subjected to acetolysis. This made no apparent difference to the speed of pollen counting but cut down the number of necessary test-tube transfers where it is suspected that much pollen can be easily lost. Only those samples from clay-gyttja or clay-peat transition zones, or from those occasional layers of peat that contain a high minerogenic influx, required the use of both techniques.

Oxidation was never used in the preparation of samples for pollen counting. The oxidation process for the removal of lignins is widely recognised as an extremely hazardous one because of its detrimental effect on pollen grains. Since the analysis of deteriorated pollen, including pollen corroded in the natural environment, forms an important part of the work in this thesis (see Chapter 6) the oxidation process was omitted from the laboratory programme at all times.

Later modifications, dictated by experience, were introduced into the laboratory preparation method. When the postglacial peats of the Amulree 1 site were found to be so extremely poor in pollen that it was necessary to count as many as seven slides when using the glacial acetic acid hydrolysis method, then the acetic anhydride method ("Erdtman's acetolysis") was tried and was found to give much more satisfactory results (Faegri and Iversen, 1964, p.71). After some experimentation with the time factor for this process (the reaction was never allowed to proceed for more than 3.5 minutes, and usually 2.0 minutes was found to be sufficient), and after some experience with the resultant modified size of the grains (pollen grains tend to be slightly enlarged when treated with Erdtman's acetolysis), this method was much preferred by the author. It has the advantages of increasing the size and greatly promoting the clarity of the patterns and processes of many of the grains, and also appears to make them more receptive to the staining medium. Erdtman's acetolysis replaced the glacial acetic acid method in the standard procedure after its successful use in the preparation of the Amulree 1 samples.

A second innovation introduced at a late stage replaced the initial HF treatment outlined above. Clay samples from Amulree 1 were found to be extremely low in pollen content. It was necessary to count up to ten slides in order to obtain a significant number of pollen grains. It was because of the Amulree clay samples that other methods for removing siliceous material were sought. Varying the time of boiling in HF gave unsatisfactory results, and boiling for more than ten minutes resulted in deterioration of pollen grains. Immersion in cold HF prior to boiling in HF was tried for durations of up to 27 hours, but again this did little to increase the pollen concentration of the material on the slides. In the recent application of HF to minerogenic material from samples collected for diagrams Amulree 2 and Mollands (where the minerogenic samples were also extremely poor in pollen content) a method described by Pennington and Lishman (1971) was copied. This method involves heating the samples in HF in polythene test-tubes for 60 minutes at 95°C. Some significant improvement was noted.

(b) Microscopy

A Vickers M15c binocular microscope, fitted with 10X Complan eyepieces and 3 Vickers Microplan lenses (10X, 40X and 100X magnifications), was used throughout this investigation. Counting was normally performed at a 400X magnification, with frequent analysis at 1000X magnification for the checking of small details in grains which were either difficult to distinguish or that could easily be mistaken for highly similar types.

When counting in the clay materials of the Lateglacial sediments, which were often extremely poor in pollen, counting was maintained at the 400X magnification at all times. No recourse to the easier method of scanning at the 100X magnification was taken for two important reasons: firstly, because deteriorated pollen were to be analysed it was important to be able to recognise the small broken parts of pollen grains which were to be counted in the "broken" class of deteriorated pollen, and which could very easily be omitted when scanning at 100X; secondly, some pollen grains on occasions displayed a tendency to be imperfectly stained and they too could be missed out when scanning at 100X (this particularly applies to Juniperus and Cyperaceae grains).

Owing to the lack of available time towards the end of this work scanning at the 100X magnification was used in the analyses of minerogenic sediments for Amulree 2 and Mollands. The analyses of deteriorated pollen, however, was not an important aspect of these particular diagrams.

(c) Pollen identification

Determination of pollen types throughout this work is mainly to the family and genus levels. A pollen reference collection is being established in the department that includes several genera from each of the families included in the various diagrams. This collection has been built from samples supplied mainly by Allergon AB of Engelholm, Sweden, and from material collected in this country by Dr. W.W. Newey (University of Edinburgh) and Mr. D.E. Caulton (Moray House College of Education, Edinburgh). All modern samples for the reference collection were prepared by treatment with hot KOH and then acetolysis, and were sealed in glycerine jelly stained with safranine aqueous. This thus allows some direct comparisons with fossil grains.

In aiding pollen identifications several text-books and papers containing excellent photographs were found useful, especially Praglowski (1962) and Erdtman, Berglund, and Praglowski (1961). The identification of unfamiliar pollen grains was according to the key in Faegri and Iversen (1964). Identification of individual species has not been possible throughout most of this work, for several reasons. The identification of species is exceedingly difficult for the pollen of several common families (this applies particularly to the families Gramineae and Cyperaceae). Even the application of electron microscopy does not resolve the difficulties encountered in recognising pollen of different grass species. The difficulties of incomplete identification for other taxa are discussed in Birks and Ransom (1969). Other difficulties are included in the fact that the reference collection is as yet far from comprehensive, and that phase contrast equipment has not been available.

Special mention should be made of the frequency graphs labelled '_Corylus_' and '_Betula_' in the pollen diagrams. It is now generally accepted that there is no obvious criteria available to permit the separation of pollen grains of _Corylus_ and _Myrica_. Many analysts now combine these genera in a composite _Corylus-Myrica_ frequency curve (e.g. Birks, H.H., 1970). Pennington _et al_. (1972) report that when separation into the two categories _Myrica_ and _Corylus_ was attempted, subsequent counts on the same traverses of the slides after an interval produced quite different results. This demonstrates how subjective any attempt to separate _Corylus_ and _Myrica_ would be. The _Corylus_ frequency graphs in those diagrams in this thesis in which it is included should be translated as composite _Corylus-Myrica_ graphs. A discussion of the possible contributions of _Myrica_ and _Corylus_ to the frequency totals is presented later (Chapter 11).

Difficulties are also encountered in attempts to separate various species of the genus _Betula_. Much argument has centred around the certainty with which _Betula nana_ grains can be separated from tree birch pollen grains, employing the three criteria of general pollen morphology, grain size, and the ratio between grain size and pore depth (Birks, 1968). Many workers were of the opinion that species of birch can be distinguished on the basis of general pollen grain morphology (Terasmäe, 1951, Erdtman _et al_., 1961; Berglund, 1966; Praglowski, 1966), but recent investigations have shown that extremely detailed biometric measurements, employing mean values of large numbers of grains, are required for certainty in this method (Berglund and Digerfeldt, 1970). Birks (1968) developed a measure of grain diameter to pore depth ratio as a means of separating _Betula nana_ grains from those of other _Betula_ species but found that although this ratio would distinguish _B. nana_ from _B. pubescens_, it would not distinguish it from _B. verrucosa_, where a measure of grain size was required instead.

In order for detailed morphometric analyses to be effective, four initial conditions are required to be met (Andersen, 1960, 1961; Berglund and Digerfeldt, 1970):-

(i) all samples must be subjected to identical chemical treatment;
(ii) all grains must be mounted in the same medium;
(iii) all slides must be of similar thickness;
(iv) all measurements should be made as soon as possible after preparation to eliminate size changes with time.

Since in this thesis such conditions were not adhered to (particularly condition (i)), and since a significant proportion of the Betula grains encountered were deteriorated or obscured in some way (grains could not be rolled or cleared from obstructions since preparations were mounted in glycerine jelly) a quantitative separation of Betula pollen grains into species has not been attempted. Tentative recognition of Betula nana grains was made during final investigations, however (e.g. Fig.25).

(d) Format of the pollen diagrams

Two basic forms of pollen diagrams are presented, in accordance with accepted conventions. For those levels indicating mainly forested conditions, where the proportion of arboreal pollen is a dominant factor in the total number of pollen counted, the relevant diagrams are based on a sum of total arboreal pollen (AP). This means that all frequency curves for pollen and spores are calculated as percentages of total AP, but the sum of deteriorated pollen is calculated according to the sum of land pollen. Percentages greater than 100 are not shown diagrammatically, but the percentage value is given next to the frequency curve. Where the arboreal pollen do not dominate in the pollen spectra, implying a non-forested environment (except where the arboreal pollen proportion is low because of over-representation of those species which contribute to the local hydrosere development), then the diagrams are constructed according to a basic sum of total land pollen.

For a more realistic picture of the historical development of the regional vegetation cover it would be more satisfactory if a 'dry land pollen' sum could be employed, resulting in a resolved diagram that excludes the complicating influx of pollen from the local hydrosere succession. This has been attempted by Walker (1966) in his diagrams relating to sites in the Cumberland lowland of North-west England. He divided the herbaceous pollen of the Lateglacial levels of his sites into separate pollen sums of 'dry land herbs' and 'damp land herbs'. Pennington (1970) points out, however, that two major difficultues exist to make such an attempt invalid:-

(i) it is difficult to classify those plants that are part of the marginal hydrosere;

(ii) some taxa of major importance (e.g. Compositae) include members of both 'dry land' and 'damp land herbs'.

Since the lowest level of identification in the diagrams presented in this thesis is, in general, at the genus level, and many identifications are only to family level, any resolution of the data according to assumed habitat requirements would be an extremely questionable procedure. All frequency curves are based, therefore, on either total arboreal pollen or on total land pollen recorded. Total land pollen includes all pollen recorded except those of obligate aquatic species, and all spores are excluded from all basic sums.

For those diagrams calculated according to an AP basic sum the AP totals varied between 100 and 200. It was decided to use a standard AP sum of 150, but this was sometimes lowered to 100 where the pollen content was very poor, and was raised to 200 where the pollen content was exceedingly high. Where the basic sum was of total land pollen the standard sum was 300 grains. It was necessary, however, to accept less than this for those levels where the pollen content was very low, often requiring the analysis of twelve slides and more for one count.

In addition to the individual frequency curves for the different taxa recognised, a separate generalised diagram, showing the collective percentages for the pollen of trees, shrubs, grasses plus sedges, and herbaceous species, is supplied for diagrams based on a total arboreal pollen sum. An argument is presented by Pennington (op. cit.) against the use of generalised percentage frequency curves for trees and shrubs in pollen diagrams representing Lateglacial sediments. The main lines of the argument are that there is a great probability that many of the tree pollen recorded in Lateglacial data result from long-distance transport to the location under study, and that many of the pollen grains recorded as tree birch pollen may in fact belong to the shrub birch form, Betula nana (see above). While the author recognises these difficult problems, and can offer no satisfactory objective solution to them, he regards generalised diagrams as being valuable in presenting to the reader a general synthesis of the main pollen types recorded, and finds them useful in a general comparison of several diagrams. The difficulties in interpretation apply to the separate frequency curves as well as to the collective ones, and what is considered by the author in the analysis of the generalised Lateglacial diagrams is the trend in the tree and shrub curves taken together.

The diagrams have all been drawn as bar graphs, the outline of each diagram following a basic uniform format to facilitate comparisons. The vertical width of each bar represents approximately the thickness of sediment used in the laboratory preparation of each sample, and this measure is related to the scale on the sediment column at the extreme left of the pollen diagrams. Similarly, the vertical thickness of the bars associated with radiocarbon dates (shown where appropriate at the extreme right of the pollen diagrams) represents the thickness of sediment collected for radiocarbon assay.

All the bar graphs are drawn to a standard scale and, in order to give an easier visual appreciation of the general trends in frequency variations, the bars are joined to give a generalised curve except where there has been a gap in the sampling. The figures that occur at the right-hand edge of some of the bars are the actual percentage figures for values in excess of 100% of the pollen sum (where AP is used) or for sudden and isolated peaks. This has been done to compress the diagrams.

The lithology symbols represented in the sediment columns are the author's, and all lithostratigraphic symbols used in this thesis are explained in the composite key of Fig. 14. Crosses in the pollen diagrams represent either isolated single occurrences of a particular taxon, or a frequency value of less than 0.5% of the pollen sum.

(e) Analysis of deteriorated pollen

During the routine counting procedure many pollen grains are observed that are in a relatively poor state of preservation, or are in some way deteriorated. 'Deteriorated pollen' refers to those grains that show visible signs of damage, usually in the pollen exine. The causes of deterioration may be complex, involving secondary redeposition, factors in transport, and factors that have affected the sediments in which the pollen have finally come to rest. Recent studies on deteriorated pollen have been concerned fundamentally with aspects of secondary redeposition (Andersen, 1954; Martin, 1958; Davis, 1961; Cushing, 1964; Birks, H.J.B., 1970), and little attention has been given to other considerations.

In late-Wisconsin (Late Devensian) pollen spectra from east-central Minnesota Cushing (1964) found that the kind and degree of pollen deterioration (and the content of secondary microfossils) were closely related to lithology. Deteriorated pollen grains were categorised and recorded during routine analysis in the present work in order to investigate quantitatively the relationship of deteriorated pollen to sediment lithology. The aim was to collect additional information that would develop interpretations based on lithology and palynology. A detailed discussion of deteriorated pollen and their interpretation is given in Chapter 6, but a short description of the assessment procedure and the categories employed is necessary at this stage, prior to a discussion of the pollen diagrams.

Cushing (1967) divided deteriorated pollen into four categories and

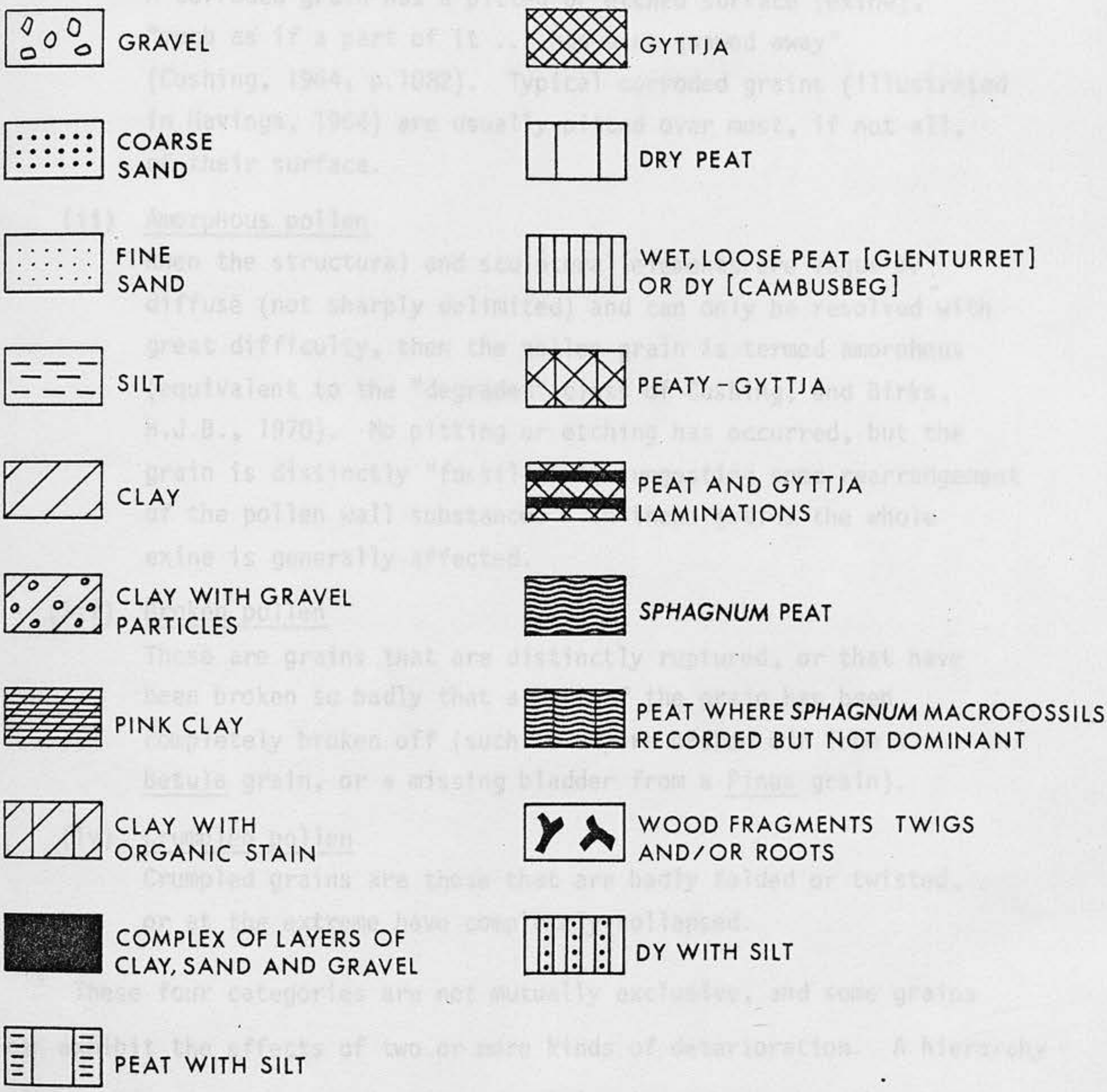


FIGURE 14 Lithostratigraphic symbols used in Figures 15-26 and 28-32.

discussed the principal causes of deterioration. The major divisions recognised by Cushing are adopted here, but his original terminology is modified in part:-

(i) Corroded pollen

A corroded grain has a pitted or etched surface (exine), "much as if a part of it ... had been gnawed away" (Cushing, 1964, p.1082). Typical corroded grains (illustrated in Havinga, 1964) are usually pitted over most, if not all, of their surface.

(ii) Amorphous pollen

When the structural and sculptural elements are vague or diffuse (not sharply delimited) and can only be resolved with great difficulty, then the pollen grain is termed amorphous (equivalent to the "degraded" class of Cushing, and Birks, H.J.B., 1970). No pitting or etching has occurred, but the grain is distinctly "fossilised", suggesting some rearrangement of the pollen wall substance. In these grains the whole exine is generally affected.

(iii) Broken pollen

These are grains that are distinctly ruptured, or that have been broken so badly that a part of the grain has been completely broken off (such as a pore broken off from a Betula grain, or a missing bladder from a Pinus grain).

(iv) Crumpled pollen

Crumpled grains are those that are badly folded or twisted, or at the extreme have completely collapsed.

These four categories are not mutually exclusive, and some grains can exhibit the effects of two or more kinds of deterioration. A hierarchy of deterioration classes, in the order i-iv given above, has thus been employed, and grains have been recorded for one class only. A grain which has been folded and ruptured, and also shows signs of corrosion, is thus recorded as a corroded pollen grain. A further division of deteriorated grains has been employed, a division into 'Indeterminable Deteriorated' and 'Determinable Deteriorated' grains. Indeterminable grains are defined as those grains whose essential features are so obscured (by any of the defined deterioration classes) that they cannot be assigned with confidence to any known pollen type. This is not the same as unknown pollen grains, which refers to those grains that may be in a perfect state of preservation, but which could not be recognised by the analyst.

The qualification and classification of deteriorated pollen are determined by extremely subjective assessments. Little is known about the precise causes of deterioration, and there is growing evidence for the differential susceptibility of pollen to deterioration and thus preservation (Sangster and Dale, 1961, 1964; Havinga, 1964, 1967). One serious difficulty, for instance, is that some grains, as modern type-slides show, characteristically display some features of deterioration. For example, Cyperaceae grains commonly have small folds at the edge of the grain, and Juniperus grains are often markedly ruptured. In such cases a decision is made as to whether deterioration can be regarded as excessive. This problem of subjectivity as well as other aspects of deteriorated pollen are discussed in more detail in Chapter 6.

(f) Frequency diagrams of deteriorated pollen

Frequency diagrams for deteriorated pollen grains are presented according to a uniform format. The sediment column and lithostratigraphic divisions described in the 'normal' pollen diagrams are repeated at the left-hand edge of Figs. 28 to 32. This in turn is followed by the frequency curve for the total amount of deteriorated pollen encountered during counting at each spectrum (curve A). Frequencies in curve A are calculated as percentages of total land pollen. A relative frequency diagram for the four basic subdivisions of deteriorated pollen - corroded, amorphous, broken and crumpled - has been calculated on the basis of percentages of the total sum of deteriorated pollen (curve B).

Frequency curves of the relative contributions of different taxa to the deteriorated pollen totals form the next major division of the diagrams (section C). These curves are only supplied for those taxa that contribute significantly to the deteriorated pollen spectra of the diagrams. Two curves are represented for each taxa, one based on the gross total of deteriorated pollen, and a second based on the total of deteriorated pollen that could be assigned to the various recognised taxa of the basic pollen diagrams (recognisable deteriorated pollen).

The last part of each diagram (sections D, E, etc.) provides an analysis of the different basic types of deteriorated pollen for those taxa that are most commonly represented in the deteriorated pollen totals. These frequency curves are based on the total number of the different genera at each level, including non-deteriorated plus deteriorated grains. For instance, the curves for Betula (total deteriorated, corroded, amorphous, broken and crumpled) are calculated on the basis of the percentage of each of these five subdivisions of the total number of birch grains (non-deteriorated plus deteriorated grains) recorded for each level. Thus section C relates the relative frequencies of different taxa to the total of deteriorated grains whilst curves D, E, etc. relate the relative frequencies of deterioration of a particular taxon to the total influx of that taxon recorded in the pollen diagram. It will become apparent that the interpretation of the curves D, E, etc. depends very much on the actual totals of pollen of these particular taxa. This varies from small insignificant numbers (where the curves become meaningless and are thus usually discontinued) to very large totals. For this reason the actual number of each taxon is supplied.

The zonation schemes given on the diagrams for deteriorated pollen (labelled at the right-hand edge of Figs. 28-32) are simply transferred from the corresponding basic pollen diagrams (Figs. 15-26). These are discussed in Chapter 4 and below. They bear no dependent relationship on the type of deterioration recorded in Figs. 28-32, but have been defined only on the basis of information supplied in the basic pollen diagrams.

2. ZONATION OF THE POLLEN DIAGRAMS

Stratigraphical sequences can be subdivided on the basis of lithology (lithostratigraphy), contained fossils (biostratigraphy), climate (climatostratigraphy), landforms (morphostratigraphy), and time (chronostratigraphy) (Mangerud, 1970). The importance of each of these criteria has varied in interpretations of stratigraphical successions in Scotland in the past, though strict chronostratigraphical division is only a very recent innovation in Scottish Late Devensian and Flandrian stratigraphy (Pennington et al., 1972; Birks, 1973; Pennington, 1975). It is chronostratigraphical considerations, however, that have demonstrated the weaknesses in inter-regional lithostratigraphic and biostratigraphic correlations (Hafsten, 1969, 1970; Hibbert et al., 1971; Pennington et al., 1972; Mangerud et al., 1974).

With regard to the Lateglacial period in Scotland Donner (1957) applied lithostratigraphic criteria as a basis for subdivision. He recognised in the sedimentary sequences of several basin sites in the Grampian Highlands and the Midland Valley of Scotland a highly organic horizon separating two layers of minerogenic sediment. These he interpreted as indicating the biostratigraphical and climatostratigraphical Jessen-Godwin zones I, II, and III (see Chapter 1). However, since lithostratigraphic and biostratigraphic horizons do not always coincide (Vasari and Vasari, 1968; Moar, 1969a) a zonation for the Lateglacial based on pollen-analytical criteria alone was eventually preferred. Moar (1969a) was the first to point out the difficulty of correlating significant changes in the pollen curves in Scottish diagrams with the accepted British zonation system first developed by Godwin (1940). His chronostratigraphic data from south-west Scotland revealed early and mid-Flandrian biostratigraphical units to be much younger in Scotland.

In an attempt to reduce confusion Moar established a system of zones "appropriate for Scotland", but recent evidence suggests that a system of Scottish pollen zones would be a gross over-simplification, so varied and asynchronous being the sequences of vegetational developments in different parts of Scotland (Pennington and Lishman, 1971; Pennington et al., 1972; Birks, 1973; O'Sullivan, 1974).

A further difficulty with interpretations of Lateglacial stratigraphy is inherent in recent demonstrations of non-agreement between lithostratigraphic, biostratigraphic, and climatostratigraphic divisions (Coope, 1970; Pennington, 1970; Pennington and Bonny, 1970; Coope and Brophy, 1972). Results published for various sites in west Britain that have been investigated in detail reveal that the Jessen-Godwin zonation scheme (Zones I, II and III), and the implications of the corresponding climatostratigraphic terms (Older Dryas, Alleröd, Younger Dryas) cannot be applied (see chapters 9 and 10). Pollen assemblages and beetle assemblages from these sites indicate relatively warm conditions (possibly with temperatures as high as those of today) long before the accepted date for the lower Alleröd boundary (11,800 B.P.), and similarly below the corresponding birch pollen zone interpreted as Zone II in the Jessen-Godwin zonation system. This led Pennington et al. (1972) to define local pollen assemblage zones for their sites in northern Scotland, and to define 'pre-Interstadial', 'Interstadial', and 'post-Interstadial' sediments. These terms have a local or regional definition only, and do not have wider ecological or climatic implications. Correlations to occurrences in other regions in Britain are based on chronostratigraphic criteria. A similar approach has been adopted by Birks (1973) for sites in the Isle of Skye.

Clearly both miscorrelation and misinterpretation can occur when employing lithostratigraphic and biostratigraphic criteria alone - miscorrelation of lithostratigraphic and biostratigraphic boundaries, and misinterpretation of stratigraphic zones in terms of climatic inferences. The method of zonation employed in this thesis is that of subdividing each pollen diagram independently on the basis of pollen assemblages alone. That is, subdivisions of each diagram are defined by stable or constant relative values of different pollen types in successive spectra irrespective of their ecological, climatic, or temporal interpretations. The difficulties with the method lie in the subjective nature of the subdivisions, especially where gradual changes in spectra occur, the unsuitability of the raw data for strict quantitative approaches, the assumption that the pollen assemblages reflect accurately regional plant communities, and the fact that changes in these pollen diagrams are dependent on relative changes in pollen influx and not on absolute changes in the influx of different pollen types (Pennington and Bonny, 1970).

One of the aims of the present study has been to construct as many Lateglacial and early Flandrian profiles as time would allow in order to derive a working hypothesis of a generalised regional zonation scheme. The necessity to reinvestigate certain sites by piston corer (see chapter 4) has limited the total number of sites investigated. However, in analysing the sediments at those sites studied it was only necessary to count as many levels as would reveal significant trends in the diagrams, and at each level to accept the lowest pollen sum that would allow statistical reliability (Faegri and Iversen, 1964). It will be shown in chapter 4 that close sampling was established for critical horizons, and that pollen sums of less than 200 had to be accepted for critical minerogenic horizons where the pollen content was exceedingly low.

In zoning the diagrams an attempt was made to take into account the general features of the pollen curves, with the important recognition of consistent changes in pollen curves, or persistent values in a pollen frequency curve. Thus a consistent rise or fall of values can be characteristic of one pollen curve in a particular zone which may be defined in terms of another curve which has altered from a previous value to a new persistent value. In other words, though some values tend to be stabilised in various parts of the diagram, there is nearly always transition. In trying to interpret the essentially transitional nature of the pollen diagrams much more emphasis is placed on those taxa that can more safely be regarded as contributors to the regional vegetational succession. Thus arboreal and shrub pollen (particularly Juniperus and Corylus) are more important in the definition of zone limits. Since Salix, Cyperaceae, Gramineae, Ericaceae, and various ferns and mosses can be important hydroseral elements, and the hydroseral development of a basin is in some respects independent of time, they are not useful indicators of changing regional vegetational patterns. In the Lateglacial horizons some use is made of the total herbaceous pollen curve, and of particular herbaceous genera (e.g. Artemisia, Filipendula, Rumex, and the spores of Lycopodium and Selaginella) in specific instances.

A comparison is made in chapter 7 of the local pollen assemblage zones, and an attempt is made to define a regional pollen zonation sequence for southern Perthshire (Table 4). Eventually it may be possible to make detailed chronostratigraphic comparisons of this regional scheme with other regional schemes, both as a check on the reliability of the generalised regional diagram, and as a basis for correlation. Some radiocarbon dates, mostly early Flandrian, are already available (chapter 9). The approximate equivalence of the Jessen-Godwin zones is given beside the local pollen assemblage zonation scheme in some of the Lateglacial pollen diagrams.

CHAPTER 4

Description of the local pollen assemblage zones and radiocarbon dates

1. INTRODUCTION

This chapter describes the biostratigraphic subdivision of the lithostratigraphic sequences described in chapter 2. Biostratigraphic subdivision is based solely on what are considered to be major changes in the composition of pollen spectra, and a brief description of each pollen assemblage zone is given, indicating the reasons for delimiting biostratigraphic horizons. The biostratigraphic sequence is then compared with the lithostratigraphy at each site. The corresponding lithostratigraphic units are given at the left hand edge of each pollen diagram, the symbols for which are explained in Fig. 14. This chapter closes with a brief discussion of the radiocarbon dates and the samples used in radiocarbon determinations.

2. TYNASPIRIT 1 (Figs.15 and 16)

The stratigraphy to which this pollen diagram relates is described in section 4 of chapter 2. Sampling was by Hiller coring equipment. The tripartite sequence of minerogenic-organic-minerogenic sediments that typifies Lateglacial deposits is clearly marked in this basin. All the sediments were consolidated and easy to sample, and they exhibited no signs of disturbance. Figure 15 presents the results of pollen analysis for the lower sediments, where the percentage curves are based on the total land pollen counted, and Fig. 16 gives that part of the pollen sequence calculated on an arboreal pollen sum. The following local pollen zones were identified:-

Tla: This zone, within the lower minerogenic sediments in the basin, is characterised by the highest representations of deteriorated pollen in the diagram (around 70% of total land pollen).

Herbaceous pollen totals are low, while <u>Betula</u> totals are consistently high. Significant inclusions of Corylus and Alnus are to be found in this zone.

T1b: In contrast to zone T1a there is a marked increase in the frequencies of Salix and certain herbaceous pollen, particularly Rumex and species of Gramineae. These coincide with marked decreases in the representation of Betula and species of Cyperaceae; Corylus pollen grains are eliminated; and totals for deteriorated pollen are depressed.

T1c: A sharp increase in Betula pollen (to around 40%) typifies this zone. This does in fact form a Betula peak in the diagram which is coincident with some of the lowest totals in herbaceous pollen and deteriorated grains, and in particular with much reduced totals of Cyperaceae, Rumex and Salix.

T1d: There is a return to the high representations of herbaceous pollen in this zone, with Rumex pollen again prominent. As deteriorated grains also increase in frequency the spectra resemble those recorded for zone T1b. Throughout T1d Betula grains decline gradually. At the beginning of the zone there is an initial influx of pollen grains of Filipendula and of aquatic species, but these totals also decline consistently throughout. Selaginella is a consistent assemblage component of this zone only.

T1e: Those trends that are apparent in the frequency curves in zone T1d are for the most part continued into zone T1e. Zone T1e is, however, characterised by an obvious peak in Juniperus pollen totals, with values in excess of 40%, which contrasts with values consistently lower than 10% in zones T1d and T1f.

T1f: With a sharp decrease in Juniperus totals there is an equally marked increase in Betula pollen which maintains high relative percentage values. Several herbaceous species disappear in this zone, while there is a marked decrease in Gramineae, Cyperaceae, Rumex, and deteriorated grains. Corylus pollen begin to increase and there is also a marked influx of aquatic pollen, particularly of Potamogeton.

Tlg: This zone is delimited by a dominant Corylus component in the pollen assemblages, with totals in excess of 100% of total arboreal pollen counted. Betula remains almost the exclusive tree component, but the appearance of Ulmus and Quercus in the diagram occurs within this zone. A sharp increase in the number of spores counted, and an accompanying gradual rise in deteriorated pollen grains, appear to herald the sharp decline in Corylus totals that determines the upper limit of zone Tlg. The generalised pollen diagram reveals that an earlier dominant tree phase (Tlf) is followed by an assemblage zone where shrubs are much more dominant.

Tlh: Corylus continues to decline in this zone, which results in a more dominant representation of arboreal pollen in the generalised pollen diagram. Of the arboreal pollen component Betula begins to lose its exclusive status, with increases in the representation of Pinus, Ulmus, Quercus and Alnus. Totals for herbaceous genera and Salix, and for deteriorated pollen grains and spores also increase in this zone. There may be some justification for subdividing Tlh since there are some contrasts above and below the 445 cm level. It is not known whether the changes recorded in the upper part of Tlh are maintained at higher levels or not since no higher samples were collected. Thus in the absence of further details a zone Tli was not delimited.

Discussion

A pronounced feature of Fig. 15 is the lack of correspondence between lithostratigraphic and biostratigraphic boundaries. Thus transition Tla/Tlb occurs where there is no apparent change in the characteristics of the lower minerogenic (clay) deposits, as does transition Tld/Tle in the upper clay deposits. Transition Tlc/Tld occurs within the organic deposits which form the middle section of the tripartite lithostratigraphic sequence, but again there is no visible change in the characteristics of this gyttja deposit. Only transitions Tlb/Tlc and Tle/Tlf approximate to lithological boundaries

In very general terms the vegetational sequence resembles that of diagrams previously published for Scotland (Vasari and Vasari, 1968; Moar, 1969a; Newey, 1970) with Rumex-dominated phases separated by a Betula phase being characteristic of Lateglacial pollen assemblage zones. Direct comparisons however cannot be made with those sites studied by Donner that are geographically closest to this site (Donner, 1957, 1958, 1962). Donner did not recognise Juniperus pollen in his analyses, nor did he analyse the minerogenic sediments from his sites. This restricts comparisons with the Lateglacial zones, even in his site Loch Mahaick, which lies only 5.5 km ENE of Tynaspirit.

A very characteristic feature of the transition from a Lateglacial treeless vegetation to a Flandrian forested landscape is a well-marked Juniperus pollen peak which is not only characteristic of Britain but of other parts of north-west Europe (Pennington, 1969; Mangerud, 1970; Hibbert et al., 1971; Birks, 1973; Smith and Pilcher, 1973). This is followed by a pioneer birch phase and then by the immigration of hazel which is usually characterised by a sharp increase to extremely high values, such as is evident in Fig. 16. The environmental implications of this immigration sequence have been discussed by Iversen (1960) and Pennington (1969), and are discussed in detail in this thesis in chapters 8, 9 and 11.

It can be assumed, therefore, that a full representation of the characteristic Lateglacial-early Flandrian vegetational sequence is recorded in the sediments at Tynaspirit. However, a major problem exists in attempting to explain the relatively high frequencies of Betula and the significant representation of Corylus in the basal zone Tla. The grains of Betula and Corylus recorded in these spectra can have one or more of the following sources:-

(a) the growth of Betula and Corylus in the local vegetation contemporaneous with the deposition of the basal minerogenic sediments;

(b) long-distance transport to the basin;

(c) the presence of secondary pollen of Betula and Corylus transported with the clay sediments to the basin;

(d) contamination of the basal sediments by organic material carried down by the Hiller coring equipment.

If (a) is accepted as the real source then this would imply an early climatic oscillation in the Callander district, in turn implying some relationship to the Bölling episode of the continent. Though the Bölling may have time-equivalent biostratigraphic data in the Coleoptera successions described by Coope et al. (1971), the possibility that the Bölling climatic amelioration was reflected in a forest expansion has been discounted for much of Britain (Pennington, 1970). There is little expansion of the curve of tree birch pollen at any horizon in deposits of the early Lateglacial Interstadial stage in north and west Britain (Pennington and Sackin, 1975) though a weakly-divided Interstadial has been recognized at some sites (Pennington, 1975). Instead Pennington (1970) attributed the presence of Pinus and arboreal Betula grains in early Interstadial deposits to the result of long-distance transfer (source (b)). Source (c) is thought to be highly unlikely in early Interstadial deposits (see chapter 6).

It is factor (d) that was initially suspected of being the source of all the Corylus grains and most, if not all, of the tree birch grains recorded in zone T1a. It is almost certain that the relatively warmth-demanding Corylus avellana was not growing in Scotland during the Lateglacial, and contamination of pre-Flandrian sediments as a result of sampling procedures has already been suggested as a source of Corylus grains recorded in Lateglacial deposits (Oldfield, 1960; Bartley, 1962, 1966). Reinvestigations employing piston corers at Tynaspirit, Amulree and Mollands (see below) have confirmed these inferences.

Figure 15 shows that _Juniperus_ is present in significant amounts, with only slight fluctuations, throughout the Lateglacial sediments. Comparison with the Tynaspirit 2 diagram (described below) suggests that the real fluctuations in _Juniperus_ in the Tynaspirit 1 diagram may have been reduced in amplitude due to the transference of pollen between different horizons in the sediments during sampling. This is an acute problem since _Juniperus_ is an important environmental indicator in pollen diagrams. Although Pilcher (1973) has demonstrated that juniper can be found today in parts of Ireland in a prostrate form growing on almost bare rock (and in conditions that are not suitable for the growth of birch), peaks in juniper pollen are usually taken to indicate a tree-line situation, or the first immigrant in a tree/shrub immigration sequence. Juniper usually heralds or is associated with immigrating birch forest (Iversen, 1960; McVean and Ratcliffe, 1962; Burnett, 1964; Vasari and Vasari, 1968; Pennington, 1969). Peaks in juniper pollen have been recorded in Lateglacial Interstadial deposits as well as in Loch Lomond Stadial-Flandrian transition deposits (Smith, 1961; Bartley, 1962, 1966; Vasari and Vasari, 1968; Moore, 1970; Pennington and Bonny, 1970; Birks, 1973.)

A further difficulty attributed to the use of Hiller sampling equipment is the fact that the lithostratigraphic sequence, because of disturbance and downward transport of material, may not have been accurately determined in detail. Comparisons of stratigraphic records determined from Hiller sampling and records obtained by enlarged piston corer are presented in chapter 2.

Although general patterns in the Tynaspirit 1 pollen diagram appear consistent and in the main logical, all of the above-outlined difficulties taken together imply that detailed analysis and comparisons within the Lateglacial records are highly questionable. It was decided, therefore, that more accurate data for Tynaspirit were necessary. The results of reinvestigations at Tynaspirit using an enlarged Livingstone piston sampler are described next.

3. TYNASPIRIT 2 (Fig. 17)

A tripartite minerogenic-organic-minerogenic basal lithological sequence was obtained in this basin (less than 100 m from the Tynaspirit 1 basin), with a gravel base located at a depth of 445 cm. The sedimentary sequence and transition horizons were again clear-cut, and the sediments were consolidated. The sampling procedures and stratigraphic results are described in detail in chapter 2.

Only the Lateglacial and early Flandrian spectra are presented in Fig. 17, and all pollen frequencies and spore frequencies are based on the total of land pollen counted. The clays that occur between 414 and 420 cm are slightly paler in colour (pale grey) than the other clays in this lithostratigraphic unit. In all other qualities they appear basically similar. However, they are almost devoid of organic remains, and much too poor in pollen content to permit significant counting. Thus there is a gap in the pollen record at these levels. The following local pollen zones were identified:-

T2a: This is a Salix-Empetrum-Rumex zone in which Compositae and Thalictrum are also important. Juniperus values increase significantly throughout this zone (from 5.0% to over 16.0%).

T2b: This zone is characterised by a sharp increase in Filipendula and Myriophyllum values, and by fluctuating curves for Betula, Juniperus and Salix. In general Salix, Empetrum and Rumex decline markedly from their earlier prominence.
The base of this zone has been radiocarbon-dated to 12,750 ± 120 B.P. (HV 4989).

T2c: A dominant Betula-Juniperus phase is now evident, with both curves achieving values in excess of 40%. This coincides with the lowest percentages for Gramineae, Cyperaceae, Rumex and other herbaceous genera in the Lateglacial spectra. Salix, Empetrum and deteriorated pollen totals are also markedly reduced.
The base of zone T2c is radiocarbon-dated to 12,395 ± 195 B.P.

(HV 4988), and the upper horizon to 11,385 ± 290 B.P. (HV 4987).

T2d: Extrapolation is necessary in this zone because of the poor pollen content of the clay samples. The most notable characteristics of this zone are the Artemisia, Rumex and deteriorated pollen curves. Betula has decreased to its smallest values in the diagram, while herbaceous taxa that had previously disappeared in zone T2c now reappear. The high Juniperus values in the upper part of this zone are discussed below.

T2e: This is a transition zone for land pollen in which Betula, Juniperus and Filipendula are increasing and Cyperaceae, Rumex and deteriorated pollen percentages are decreasing. Empetrum and Gramineae are also important in this zone. In addition, within this zone there is a very marked increase in the aquatic pollen influx, from less than 10.0% to values in excess of 80%.

The upper horizon of this zone is radiocarbon-dated to 10,420 ± 160 B.P. (HV 4985).

T2f: This is a Betula-Juniperus phase in which, however, Juniperus is declining in importance. Many herbaceous genera disappear in this zone but Filipendula increases in its representation.

T2g: This Betula-dominated assemblage zone is also notable for the first significant appearance of Corylus in the pollen diagram. A radiocarbon assay of the uppermost organic deposits collected for this site (370 cm below surface) gave a date of 9,260 ± 100 B.P. (HV 4984).

Discussion

In comparing Tynaspirit 2 with the pollen diagram for Tynaspirit 1 (above) six points are here selected. Other aspects are included in the fuller discussions in chapters 7 and 8. These six are:-

(i) Lithostratigraphic and biostratigraphic boundaries

It was noted (above) that most lithostratigraphic boundaries in Tynaspirit 1 do not coincide with major biostratigraphic boundaries. In contrast, the transitional gyttja sediments of Tynaspirit 2 (lithostratigraphic units 4, 6 and 8, Fig. 17) all coincide with important biostratigraphic boundaries. However, the boundary T2b/T2c occurs where there is no apparent lithostratigraphic change (within lithostratigraphic unit 5).

(ii) The Juniperus curve

Juniperus is more strongly represented in Tynaspirit 2 than in Tynaspirit 1. This may reflect differences in the influx components at the two sites, or the bolder and more straightforward trends in the Tynaspirit 2 diagram might suggest possible distortion of the curve in Tynaspirit 1.

(iii) The Corylus records

Not a single grain of Corylus is recorded below 400 cm at Tynaspirit 2, i.e. no grains are recorded within the basal tripartite lithostratigraphic sequence. If the basal sequences at both sites are to be regarded as synchronous (as has been implied throughout this chapter) then this alone very strongly suggests contamination in the Tynaspirit 1 diagram.

(iv) The Empetrum records

Two definite peaks of Empetrum occur in Tynaspirit 2, both peaks immediately preceding a dominant Betula-Juniperus phase. This pattern is not evident in Tynaspirit 1.

(v) The Artemisia records

Artemisia is strongly represented in one zone, T2d, where it achieves a peak at 10.0%. The tendency appears to be similar but not nearly so emphatic in Tynaspirit 1. The difference may lie in the fact that closer sampling at Tynaspirit 2 better represents this phase in the diagram.

(vi) The curves for aquatic pollen

The contrasts and general trends within the curves for aquatic pollen, particularly Myriophyllum and Potamogeton, are much more emphatic in the Tynaspirit 2 diagram. The sharp increases in aquatic pollen occur immediately prior to the increases in Betula and Juniperus in the diagram. Again this may relate to extremely local variation in floral composition, possibly due to differences in base status of the lake waters, but other evidence discussed above suggests that the more likely causes are distortion of the Tynaspirit 1 records and the wider sampling intervals used there.

That the basal deposits at Tynaspirit 1 and Tynaspirit 2 span the Lateglacial and early Flandrian periods is confirmed by the radiocarbon dates which range from ca. 12,750 B.P. to ca. 9260 B.P. The general trends of vegetational development are basically similar in the diagrams from Tynaspirit 1 and Tynaspirit 2, with the exception of the Corylus records. Thus the pattern of two dominant Rumex phases separated by a Betula-dominated phase is recorded at both sites. In addition the fluctuations of the deteriorated pollen curves are basically similar, and bear the same relationship to the lithostratigraphic sequence, with the high frequencies of deteriorated pollen coinciding with the minerogenic layers. However, the pollen frequency changes and overall trends are much clearer and easier to interpret in the Tynaspirit 2 diagram than in Tynaspirit 1, demonstrating that the former diagram represents more accurately the vegetational sequence in the Lateglacial and early Flandrian of the Teith Valley. The diagrams from Tynaspirit 1 and Cambusbeg (discussed below) are heavily distorted owing to the sampling mechanism of the Hiller. The presence of Corylus grains in pre-Flandrian deposits is the best indicator of contamination by this means, but the six points of comparison reviewed above, when considered together, suggest distortion of the pollen frequency curves as well as contamination at Tynaspirit 1.

4. CAMBUSBEG (Figs. 18 and 19)

In contrast to the sediments of the Tynaspirit basin those at Cambusbeg are extremely soft. The basal layers are described in detail in chapter 2, and from this description it is clear that the straightforward tripartite sequence of minerogenic-organic-minerogenic basal sediments exhibited at Tynaspirit is not repeated in the Cambusbeg kettle-hole. The Flandrian organic muds, dy deposits, are also complicated by a series of thin minerogenic layers within them.

Figure 18, related to the lower-most metre of sediments, presents the results of pollen analysis calculated on the basis of a total land pollen sum. Analyses from the upper organic deposits (Fig. 19), where the combined tree and shrub frequency remains consistently in excess of 50% of total land pollen, are calculated with an arboreal pollen sum. The following local pollen assemblage zones are identified:-

Cla: This includes the two spectra at the base of the diagram and it is mainly delimited by contrast to zone Clb. It is, however, characterised by two of the highest values for deteriorated pollen.

Clb: Sharp increases in herbaceous pollen, particularly _Rumex_ and species of Compositae, are accompanied by more gradual increases in _Betula_ and _Myriophyllum_ pollen. _Rumex_ forms a peak in the diagram in this zone. Deteriorated pollen decline from their previous high values.

Clc: Gradual increases in _Betula_ and _Juniperus_ pollen contrast with gradual declines in herbaceous pollen (particularly _Rumex_ and Gramineae) throughout this zone. Peaks in _Empetrum_ and _Corylus_ (rising to about 10%) also occur, and in this zone the lowest values for deteriorated pollen within the minerogenic sediments are recorded.

Cld: This zone is mainly delimited by a marked peak (up to 35%) in the _Betula_ pollen curve. It is associated with lows in the curves of Cyperaceae, _Rumex_, and the total herbaceous pollen curve. Some difficulty is encountered in accounting for the pattern of _Juniperus_ and _Corylus_ (discussed below).

Cle: A juniper peak occurs within this zone, but it is associated with increased frequencies of _Rumex_, Cyperaceae, other herbaceous genera, and deteriorated pollen, following the marked decline of all of these components in Clc. In addition, Artemisia and Selaginella become much more significant in this zone, while Betula totals decline throughout.

Clf: This is a transitional zone in which Betula increases gradually to values in excess of 50% and herbaceous totals, Cyperaceae in particular, and deteriorated pollen frequencies, gradually decline. Empetrum and Salix values increase again, and many herbaceous genera finally die out in this zone (Galium, Dryas, Urtica, Plantago, and Saxifragaceae). Juniperus and Corylus values fluctuate.

Clg: This zone, similar to zone Clf in many respects, is a Betula-dominated phase, with the highest relative arboreal pollen totals recorded at this site.

Clh: As with the Tynaspirit sequence, the Betula phase is replaced by a dominant hazel phase with all percentages of Corylus in excess of 100% of total arboreal pollen. Also in agreement with diagram Tynaspirit 1, the first consistent appearances of Ulmus, Quercus, and Alnus are associated with this phase, resulting in the first challenge to the exclusive dominance of birch in the tree component.

Cli: A much reduced Corylus content (70% or less), is, as at Tynaspirit, coincident with a sharp increase in the relative frequency of deteriorated pollen grains. Betula continues to decline gradually as Quercus increases slightly.

Clj: This is an Alnus-Quercus-Corylus phase, not represented in the Tynaspirit 1 diagram (Fig. 16). Alnus and Quercus are now firmly established, while Corylus (40%-80%) and Betula (values greater than 25%) continue to be significantly represented. From the generalised pollen diagram (Fig. 19) it is noticeable that the shrub-dominated assemblages have now given way to tree-dominated spectra.

Discussion

In the Cambusbeg diagram there is again no strict correspondence between lithostratigraphic and biostratigraphic boundaries. In addition to there being no clear tripartite sedimentary sequence there is also a confusing pollen zonation sequence in the lower sediments (Fig. 18) which bears some resemblance to patterns in the Tynaspirit diagrams, but in other respects differs quite markedly. It should here be stressed that the zone limits marked in Fig. 18 are extremely subjective and might differ substantially from the divisions delimited by other analysts. They are denoted principally for use as guide-lines for the arguments that follow.

The doubts as to the suitability of Hiller equipment for sampling for pollen analysis in Lateglacial sediments is not only based on the comparison of the Tynaspirit diagrams, described above, but is substantiated by the results of later investigations at Amulree and Mollands (discussed below). Problems of stratigraphic disturbance and contamination due to the downward transport of organic material can be demonstrated at each site where comparisons can be made between diagrams based on Hiller samples and diagrams based on piston-sampler cores (Tynaspirit, Amulree and Mollands). It is almost certain, therefore, that the vegetational sequence in Fig. 18 is heavily distorted. Problems of disturbance and downward contamination must be even more severe at a site such as Cambusbeg, where the sediments are so extremely unconsolidated throughout.

In making comparisons with the basal sequence at Tynaspirit there are two possible interpretations of the basal pollen assemblage zones at Cambusbeg:

(i) that pollen zones Cla-Clf record a Lateglacial sequence of pollen zones similar in outline to that at Tynaspirit (zones Tla-Tle), but badly distorted and contaminated;

(ii) that pollen zones Cla-Clf represent a distorted early Flandrian transitional zone equivalent to, say, zones Tld and Tle only.

In support of the first hypothesis are some of the general trends discernible from Fig. 18. Thus the Rumex curve is dominant in early spectra and this gives way to a Betula peak which in turn is followed by a zone where the Rumex representation has increased again. The pattern in Rumex is mirrored by the general fluctuation of the total herbaceous pollen frequency curve throughout zones C1b-C1f. The deteriorated pollen frequency curve is also basically similar in outline to the corresponding curve in the Tynaspirit diagram, with much reduced values corresponding to the reduction in Rumex frequencies, but with sharply increased values coincident with the upper Rumex zone. The increased Artemisia and Selaginella values in zones C1e and C1f could be interpreted as indicating cold Loch Lomond Stadial conditions (Pennington et al., 1972), but both closer sampling and absolute pollen counting would be required in order to determine the real significance of the increased values of Rumex, Artemisia and Selaginella in this part of the diagram.

However, this first hypothesis conflicts with the evidence of the fluctuating Juniperus content, which achieves its highest values in zone C1e, and with the fluctuating curve for Corylus, which is present in significant amounts throughout zones C1c, C1d and C1e. If one regards the Betula and Juniperus curves together and independently from the other curves in the diagram then one could arrive at a different interpretation. Taking into consideration the possibility that the reduction in Betula representation that occurs in zones C1e and C1f is not climatically controlled but is a statistical consequence of variations in the actual Juniperus pollen influx, then this could suggest that in absolute terms the Betula frequency values may continue to increase gradually throughout zones C1a to C1f. This would imply that the whole sequence is a distorted representation of an early Flandrian transition phase.

In order to resolve some of these difficulties attempts were made to reinvestigate the Cambusbeg site. Sampling by means of an enlarged piston corer (Abbey piston sampler) proved unsuccessful as the sampling chamber would not retain the extremely soft basal sediments. Equally unsuccessful were attempts to use a Russian peat corer. Only partial cores were obtained, and these were obviously badly distorted. In order to investigate the detailed stratigraphy and undisturbed pollen sequence of these sediments it would be necessary to employ such sophisticated equipment as the corer developed by M. Saarnisto (personal communication) for freezing sediments in situ.

In attempting to reconstruct the Lateglacial environment from vegetational developments (chapter 8) much more emphasis will be placed on the results of investigations at Tynaspirit, where the deposits at Tynaspirit 1 are much more consolidated and where more detailed analyses are available for Tynaspirit 2. Nevertheless the author is of the opinion that the first of the two hypotheses outlined above is the more likely explanation of zones C1a-C1f. The increase of Rumex, Artemisia and Selaginella suggests a return to more open vegetation, and the presence of these taxa and the marked increase in deteriorated pollen in zone C1e (see chapter 6) suggest disturbed soil conditions. Supposing zones C1a-C1f to represent a transitional Loch Lomond Stadial-Flandrian phase (when organic deposition and pollen influx would be increasing in the basin), it would seem unlikely that the increased values of Rumex, Artemisia and Selaginella, and of deteriorated pollen, were all a result of statistical variation in a relative frequency diagram. Zones C1b-C1c are interpreted as Lateglacial Interstadial zones, and the base of zone C1f as the base of the Flandrian. The Lateglacial Interstadial-Loch Lomond Stadial boundary is difficult to identify because of the amount of distortion of the pollen spectra. The presence of Corylus contradicts the general ecological interpretations of zones C1c-C1e, and it must therefore indicate very serious contamination at this site. This is confirmed by the presence of Quercus and Ulmus pollen in these zones.

The upper pollen assemblage zones Clg, Clh and Cli, exhibit clear similarities to zones Tlf, Tlg and Tlh. Of particular note is the pronounced Corylus phase recorded at each site, and the sharp increase in the proportion of deteriorated pollen grains which coincides with the decline of Corylus at both sites (transitions Clh/Cli and Tlg/Tlh). The upper-most Alnus-Quercus-Corylus zone at Cambusbeg (Clj) is not recorded in the analysed sediments of Tynaspirit. Because of the close agreement in these zones it is concluded that distortion of pollen assemblage zones by contamination by pollen from higher (and younger) deposits is not as severe a problem in the Flandrian organic sediments as it is in the Lateglacial sediments, particularly in minerogenic deposits.

5. AMULREE 1 (Figs. 20 and 21)

A large Hiller sampler was employed during initial investigations at Amulree. The deepest part of the basin, 12.0 m, contained over 8.0 m of peat and just under 4.0 m of stiff clay deposits. Although this basin lies outside Thompson's (1972) limit for the Loch Lomond Readvance ice in this area (see Fig. 7) a basal tripartite sequence was not discovered. Instead ca. 4.0 m of extremely compacted clay deposits were recorded at the base, underlain by coarse gravel deposits. The clays varied in their degree of compaction and in colour (detailed description, chapter 2). The mottles of pink colouration recorded for lithostratigraphic unit 5 (Fig. 20) could not be explained, and this was one of the reasons for the decision to reinvestigate this site (see Amulree 2, below).

The clays were found, in general, to be extremely poor in pollen. It was decided to use a minimum land pollen sum of 200, but even this had to be reduced where counting of more than 10 slides was required to achieve a significant total of land pollen. A maximum number of 15 slides was counted for any one level. Those levels that do not record 200 land pollen or more (see basic sum column, Fig. 20) give some indication of the variable pollen content of the clays. Other levels, particularly below

10.0 m depth, had to be abandoned because of the poor pollen content.

Two diagrams cover the pollen assemblage sequence of Amulree 1. Figure 20, related to the basal clay deposits and the clay-peat transition, is based on a total land pollen sum, and Fig. 21 is based on an arboreal pollen sum. The following local pollen assemblage zones were identified:

Am1a: The pollen content of lithostratigraphic unit 1 (Fig. 20) is too low for pollen counting to be acceptable. However, as soon as the clay colour changes from pink to grey (lithostratigraphic unit 2) the pollen influx increases relative to clay deposition. Initial pollen spectra indicate a predominantly herbaceous community, with Salix and Empetrum pollen also quite significant.

Am1b: Rumex increases markedly at the Am1a/Am1b transition, but thereafter gradually decreases from its highest value of 17%. Herbaceous totals are higher in zone Am1b than in Am1a, while Salix and Empetrum are much reduced. Also of significance throughout zone Am1b are the increased proportions of Lycopodium and Selaginella, and the gradual increase in the number of genera counted in the herbaceous pollen totals (the number of genera recorded almost doubles in the upper part of Am1b). This zone is designated a Cyperaceae-Rumex-Lycopodium-Selaginella zone.

Am1c: In this zone Betula and Juniperus increase markedly to double the values achieved in zone Am1b (Betula from ca. 10-12% to a peak of 24% and Juniperus from ca. 5-9% to a peak of 17%). Cyperaceae, Rumex and Selaginella are reduced but there are major fluctuations in Lycopodium and in herbaceous pollen totals. The amount of deteriorated pollen, which in general increases throughout Am1b, is reduced in Am1c but also fluctuates within this zone. The increases in Betula and Juniperus are also accompanied by slight increases in Salix and Empetrum totals.

Amld: The tendency to increased representation of Betula and Juniperus is in this zone very much reversed, Betula fading to a value of 5% and Juniperus to 7%. Herbaceous pollen and deteriorated pollen increase to values as high as those recorded in Amlb, with notable re-expansions of Cyperaceae, Rumex, and to a lesser extent Lycopodium and Selaginella. The zone is marked by the highest consistent values of Artemisia, and by a peak in the Ranunculaceae species.

Amle: The frequency curves above zone Amld are very difficult to interpret. Although around the Amld/Amle boundary Betula, Juniperus, Salix and Empetrum all increase significantly, they decline sharply again to give way to re-expansions of Gramineae, Cyperaceae, herbaceous pollen and Filicales spores. Zone Amle is treated here as a transitional zone between the herbaceous community of Amld and the Betula-Juniperus zone Amlf, but clearly this zone, which coincides with lithostratigraphic transition 9-10, requires much more detailed inspection (see section 6).

Amlf: This is a Betula-Juniperus zone which includes a juniper peak of over 146% of total arboreal pollen (Fig. 21). In this zone aquatic pollen, especially Myriophyllum and Potamogeton, and Dryopteris spores, increase markedly.

Amlg: The curve for Corylus pollen increases to give values of between 92% and 115% of arboreal pollen totals. Birch still accounts for about 90% or more of the arboreal pollen.

Amlh: Corylus begins to lose its continuous dominance of the diagram in this zone. This zone is also marked by a significant reduction of Betula due to a marked increase of Ulmus pollen and also smaller increases in Pinus, Quercus and Alnus.

Amli: There are three major characteristics of this assemblage zone:

(i) the predominance of arboreal pollen in the pollen spectra (see the generalised pollen diagram following the column of arboreal pollen sums in Fig. 21), in which Betula increases slightly from those values recorded in Amlh;

(ii) a marked reduction of Corylus pollen;

(iii) a marked increase in the amounts of deteriorated pollen grains coincident with the sharp reduction in Corylus totals.

Zones Amlj-Amlm

These zones are difficult to delimit. At the Amli/Amlj boundary there is a transition in the diagram to the predominance of taxa that can be regarded as extremely local to the basin, or, specifically, as contributors to the natural seral succession in and around the basin. Thus Sphagnum moss, which had begun to expand in Amlg and Amlh, Cyperaceae, and the dwarf shrubs of the Ericaceae family and of Empetrum, all expand significantly in the upper four zones of the diagram. Zones Amlj-Amlm are delimited on the basis of the ratio of Corylus pollen to arboreal pollen, and of fluctuations within the arboreal pollen totals:-

Amlj: A significant increase in Corylus occurs here, and a slight increase in Pinus.

Amlk: Pinus increases sharply, while Corylus declines once more.

Amll: A return to high Betula frequencies occurs in this zone, and there is some increase in Corylus totals.

Amlm: Corylus now dominates the pollen spectra once more, while significant increases in Pinus, Quercus, Ulmus and Alnus all contribute to a major reduction in the dominance of Betula in the arboreal pollen component.

Discussion

Though there is no basal tripartite lithostratigraphic sequence at Amulree, there are nevertheless major biostratigraphic subdivisions apparent in the basal pollen spectra. Thus zones Amla to Amlc can be interpreted as indicating the development of a closed vegetation cover, culminating in the introduction of juniper shrub and dwarf birch or possibly tree birch into the area. This tendency towards the development of a closed vegetation is reversed in zone Amld. Whether or not these contrasts in pollen assemblages are to be equated with Lateglacial climatic changes is discussed in chapter 8, but it is sufficient to point out here that the absence of lithostratigraphic variation does not necessarily mean that major biostratigraphic changes are not taking place. Transitions Amlb/Amlc and Amlc/Amld do not equate with any recognisable lithostratigraphic changes.

Some points of comparison can be made between the lower biostratigraphic zones of Amulree 1 and the basal zones of Tynaspirit 1, Tynaspirit 2 and Cambusbeg. Thus an initial Rumex phase which is replaced by a Betula-Juniperus phase, which in turn gives way to spectra indicating re-expansion of Rumex in association with the highest representation of Artemisia in the respective diagrams, is a pattern common to each pollen diagram (Figs. 15, 17 and 18).

There are, however, several points that made it necessary to reinvestigate the basal five metres of deposits at Amulree (see Amulree 2 below). Firstly, the presence of Corylus pollen has already been shown to indicate contamination of Lateglacial sediments. Some Corylus pollen has been discovered at almost every level in the basal deposits of Amulree 1. Secondly, the grey clays with mottles of pink clay recorded in lithostratigraphic unit 5, and the variable pink clays recorded in lithostratigraphic units 3 and 8 (see chapter 2) do not provide any clear pattern, and this suggested distortion of the original sediment pattern. Thirdly, as has already been mentioned, the transition assemblage zone Amle is difficult to interpret, possibly suggesting some biostratigraphic distortion or an inadequate number of pollen spectra. It was therefore decided to reinvestigate the Amulree site using a piston corer. In addition, some chronostratigraphic correlation between Amulree and sites in the Teith Valley was necessary, and an enlarged piston corer was required for the collection of samples for radiocarbon assay.

In the upper organic deposits some comparisons can be made between Amulree and Tynaspirit and Cambusbeg in the delimitation of a Betula-Juniperus zone (Am1f, C1f, T1f, T2f) and a Betula-Corylus phase (Am1g, C1h, T1g). However, Amulree 1 resembles the Tynaspirit 1 diagram in that a dominant Betula phase with minor quantities of Juniperus and Corylus (C1g, T2g) is not fully developed. The Corylus rise follows almost immediately after the Juniperus peak. It may be that this zone is represented by level 775 cm at Amulree 1 and by levels 550 cm and 560 cm at Tynaspirit 1, and that the lack of development of this zone is a result of the relative rate of deposition of organic deposits at these two sites. However, the pattern at Amulree is interpreted as indicating vegetational contrasts between Amulree and sites in the Teith Valley (see chapters 7 and 8).

The sudden rise in the proportion of deteriorated pollen grains at the termination of the Betula-Corylus phase at Amulree 1 is a pattern that has already been noted at Tynaspirit 1 and Cambusbeg (above). The immigration of Quercus, Ulmus and Alnus offers further points of comparison.

6. AMULREE 2 (Fig. 22).

The deposits at Amulree were reinvestigated using an Abbey piston corer of 5.0 cm internal diameter. Penetration below 1075 cm was impossible with the large chamber of the Abbey and even with the small piston chamber (internal diameter 2.0 cm) of the Dachnowski piston sampler. The stiff basal clays at Amulree could only be sampled using a Hiller, where penetration is aided by the auger mechanism. Thus the pollen spectra between 1075 cm and 1200 cm in the Amulree 1 diagram could not be checked.

Numerous very distinct clay rhythmites, sometimes alternating in colour between grey and pink, were recorded from the cores collected by the Abbey corer (lithostratigraphic units 1 and 2, Fig. 22). These proved the sediments recorded for Amulree 1 to have been severely distorted. The sediment record for Amulree 1 is described in detail in chapter 2, and a fuller comparison of the Amulree 1 and Amulree 2 sediments is developed in chapter 5.

Figure 22 presents the results of pollen analysis for the basal clays and the clay-peat transition. The diagram is based on a pollen sum of total land pollen. Because of the extremely poor pollen content of the basal clays (see Amulree 1 above) a pollen sum of 200 land pollen was employed, with the exception of the three lowermost levels where extreme scarcity of pollen necessitated a reduction of the sum to 100 land pollen. The pollen sum was increased for organic-rich samples, and was particularly high for those spectra dominated by Juniperus pollen in order to obtain significant totals of other taxa.

The following local pollen assemblage zones were identified:-

Am2a: This zone is dominated by spores of the clubmosses Lycopodium and Selaginella. Herbaceous pollen grains dominate the pollen sums with Cyperaceae significant throughout and an early Artemisia-Caryophyllaceae phase giving way to rising frequencies of Rumex. Also of note in this zone are the high percentages of Pinus pollen recorded at some levels. At one level Pinus accounts for 20% of total land pollen.

Am2b: This is a herbaceous pollen assemblage zone with constant frequencies throughout. It is a Rumex-Cyperaceae-Gramineae zone, with Ranunculaceae and Caryophyllaceae also important. Selaginella, Lycopodium and Artemisia are still significantly represented.

Am2c : This zone is still basically a Rumex-Cyperaceae-Gramineae zone, but there are some important contrasts with Am2b. Firstly, Rumex achieves its highest consistent values in the diagram in Am2c, while the herbaceous pollen totals are lowest in this zone. Caryophyllaceae in particular are very much reduced. Secondly, the deteriorated pollen totals decrease consistently throughout zones Am2b and Am2c. Thirdly, there are significant representations for the first time of Juniperus and Empetrum.

Am2d: Lycopodium spores increase markedly at the Am2c/Am2d boundary, in addition to a smaller increase of Selaginella spores. Rumex, Cyperaceae and Gramineae values all decrease, and Juniperus records almost die out. Also of note in this zone are the increased percentages of Pinus and Betula.

Am2e: This zone is notable for the highest consistent percentages of herbaceous pollen in the diagram. Of particular note in these totals are the relatively high percentages of Artemisia and Caryophyllaceae. These taxa account for much of the reduced importance of Rumex, Cyperaceae and Gramineae. Salix values also increase in Am2e, and, though they have not been represented in a separate curve, many of the grains recorded were of the Salix herbacea type. Empetrum and Juniperus totals are insignificant in this zone, but Pinus and Betula continue to be important components of the pollen spectra. An additional characteristic of Am2e is the marked rise in the curve for deteriorated grains in the upper part of the zone.

Am2f: Major changes in the pollen spectra occur in this zone, with Gramineae, Cyperaceae, Empetrum, Salix, Juniperus and aquatic pollen all becoming important. The herbaceous totals, the curves for the clubmoss spores, and the frequencies of deteriorated grains all decline steadily throughout Am2f. Pinus totals are also very much reduced.

The middle part of this transitional zone, where a Rumex-Cyperaceae assemblage zone gives way to a Juniperus-Empetrum phase, has been radiocarbon-dated to 10,770 ± 90 B.P. (HV 5644).

Am2g: This is a Betula-Juniperus zone which also records a major increase in the aquatic vegetation in the Amulree lake. The base of the zone, marking the main expansion of juniper, has been radiocarbon-dated to 10,270 ± 100 B.P. (H V 5643), and the upper part of the zone, marking the decline of juniper and the first consistent representation of hazel, has been radiocarbon-dated to 9,115 ± 120 B.P. (HV 5642).

Discussion

In general there is good overall agreement in the spectra recorded for zones Am2a-Am2g of Amulree 2 and zones Am1b-Am1f of Amulree 1. This can be seen most readily in the curves for Artemisia, Rumex, Caryophyllaceae, Lycopodium and Selaginella. There are, however, a number of important differences:-

(i) the Betula and Juniperus totals are in general higher in the clay samples of Amulree 1 and form more accentuated peaks than in Amulree 2;

(ii) the Gramineae and Cyperaceae totals are much higher in the Amulree 1 diagram than in Amulree 2;

(iii) the percentages of Compositae are higher in Amulree 1 than in Amulree 2;

(iv) Artemisia and Caryophyllaceae achieve much higher totals in the Amulree 2 diagram than in Amulree 1;

(v) the number of deteriorated grains recorded is in general much higher in Amulree 1 than in Amulree 2;

(vi) Corylus is only recorded at two levels in the clay deposits of Amulree 2, but is recorded throughout the clay samples of Amulree 1.

The differences between these two diagrams can be explained by the effects of two important variables, firstly, the relative amount of contamination in the samples, and secondly, the variation in pollen influx that occurs throughout the basin sediments. It is highly unlikely that two diagrams resulting from separate samples from the same site would be exactly alike, though diagrams Amulree 1 and Amulree 2 are broadly similar.

The contamination caused by the Hiller chamber, as described for the Tynaspirit 1 deposits above, must also have affected the Amulree 1 deposits. This would explain the records of Corylus, the decreased amplitude of the Artemisia and Caryophyllaceae curves, and possibly the increased amplitude of the Betula and Juniperus curves (though this is more difficult to explain (see chapter 7)) in the Amulree 1 diagram. Though the Betula and Juniperus curves do increase in Amulree 2 in zones Am2d and Am2c respectively, they do not increase to the same degree as in Amulree 1. However, contamination would not explain the differences in the Gramineae and Cyperaceae curves, nor the contrast in the frequencies of deteriorated grains. This variation is best explained as a statistical consequence of local variation in pollen influx within the sediments.

In addition to the evidence for lithostratigraphic distortion in the Amulree 1 sediments (described above), the Amulree 2 diagram provides evidence of biostratigraphic distortion. However, the sediment records and pollen diagrams resulting from both boreholes are in agreement in demonstrating that though there is no lithostratigraphic evidence for Lateglacial climatic fluctuations there is biostratigraphic evidence. Though the Betula-Juniperus zone that characterises the upper part of the Lateglacial Interstadial period at Tynaspirit and Cambusbeg is not well developed in Amulree 2, and may be exaggerated by the results of biostratigraphic distortion in Amulree 1, there is nevertheless evidence from both diagrams for the break-up of closed vegetation communities and a return to disturbed soil conditions (zones Am1d, Am2d, Am2e). This vegetational pattern, its relation to other pollen diagrams, and its environmental implications are fully discussed in chapters 7 and 8.

In the Amulree 1 pollen diagram the early Flandrian zone Am1e is characterised by reductions in percentages of Betula, Juniperus, and Empetrum, and notable increases in percentages of Gramineae, Cyperaceae, Rumex, and Ranunculaceae. This suggests a minor vegetational revertence phase following that of the Loch Lomond Stadial (zone Amld). However, since this pattern is not represented in the Amulree 2 diagram, it seems probable that the fluctuations in the Amulree 1 diagram are apparent, resulting from contamination of Loch Lomond Stadial clays. Thus the initial increases in percentages of Betula, Juniperus, and Empetrum pollen and the significant representation of Corylus towards the top of zone Amld may reflect contamination of the upper clays of lithostratigraphic unit 9, which are poor in pollen content, by pollen grains carried from pollen-rich peat (lithostratigraphic unit 10) by the Hiller chamber.

The radiocarbon dates from Amulree indicate that the lowest organic deposits at this site relate to the Loch Lomond Stadial/Flandrian transition period. This strongly suggests that the biostratigraphic variations identified in the clays below the dated horizons are related to environmental changes during the Lateglacial period, and thus the vegetational revertence phase identified in both Amulree 1 and Amulree 2 is equated with the Loch Lomond Stadial. Further, the 4.0 m of clay deposits at this site, including a large number of thin laminations, imply sedimentation over a long period of time (see chapter, 5, section 5).

7. MOLLANDS (Figs. 23, 24 and 25)

Three pollen diagrams are available for Mollands, each based on the analysis of samples collected by different peat corers. Initial sampling of the basal minerogenic deposits was by small Hiller, as it was not possible to penetrate more than a few centimetres the minerogenic sediments with the large Hiller. The organic deposits at Mollands were sampled by the large Hiller, and the minerogenic sediments were later analysed in detail through cores collected by the Abbey piston corer. The sediment records are fully described in chapter 2.

A. Samples collected by small Hiller (Fig. 23)

Figure 23, a preliminary pollen diagram for the basal deposits at Mollands, has not been subdivided. The significant percentages of *Corylus* within the minerogenic sediments that are believed to have been laid down immediately after the retreat of the Loch Lomond Stadial ice from the Callander area suggested to the author the possibility of contamination. Since there is evidence for contamination and stratigraphic distortion in samples collected by large Hiller (see sections 3, 4 and 6 above) the pollen spectra in Fig. 23 were regarded as highly questionable. Zoning of the diagram was avoided until further material was available (see section C below).

B. Samples obtained by large Hiller (Fig. 24)

Attempts were made to obtain a complete sequence of cores for the deepest part of the basin using a large Hiller corer. Unfortunately great difficulty was experienced in penetrating the minerogenic sediments; hence Fig. 24 presents the results of pollen analysis for the peat and gyttja deposits only. The upper 50 cm of the organic deposits are not included in this diagram since this consisted of modern root growth and decayed roots. The zonation of this diagram was completed after the results of investigations of the lower minerogenic sediments and the zonation of Fig. 25. This explains why the first zone at the base of Fig. 24 is labelled Mob. Figure 24 is based on an arboreal pollen sum. The following local pollen assemblage zones were identified:-

Mob: This is a *Betula*-*Juniperus* zone in which *Filipendula* is an important contributor to the pollen influx. The fern *Dryopteris* is also important.

Moc: This is a *Betula*-dominated zone where arboreal pollen (mainly birch) contribute over 60% of the total land pollen recorded. A small *Corylus* fluctuation, with a peak at about 20%, occurs within Moc.

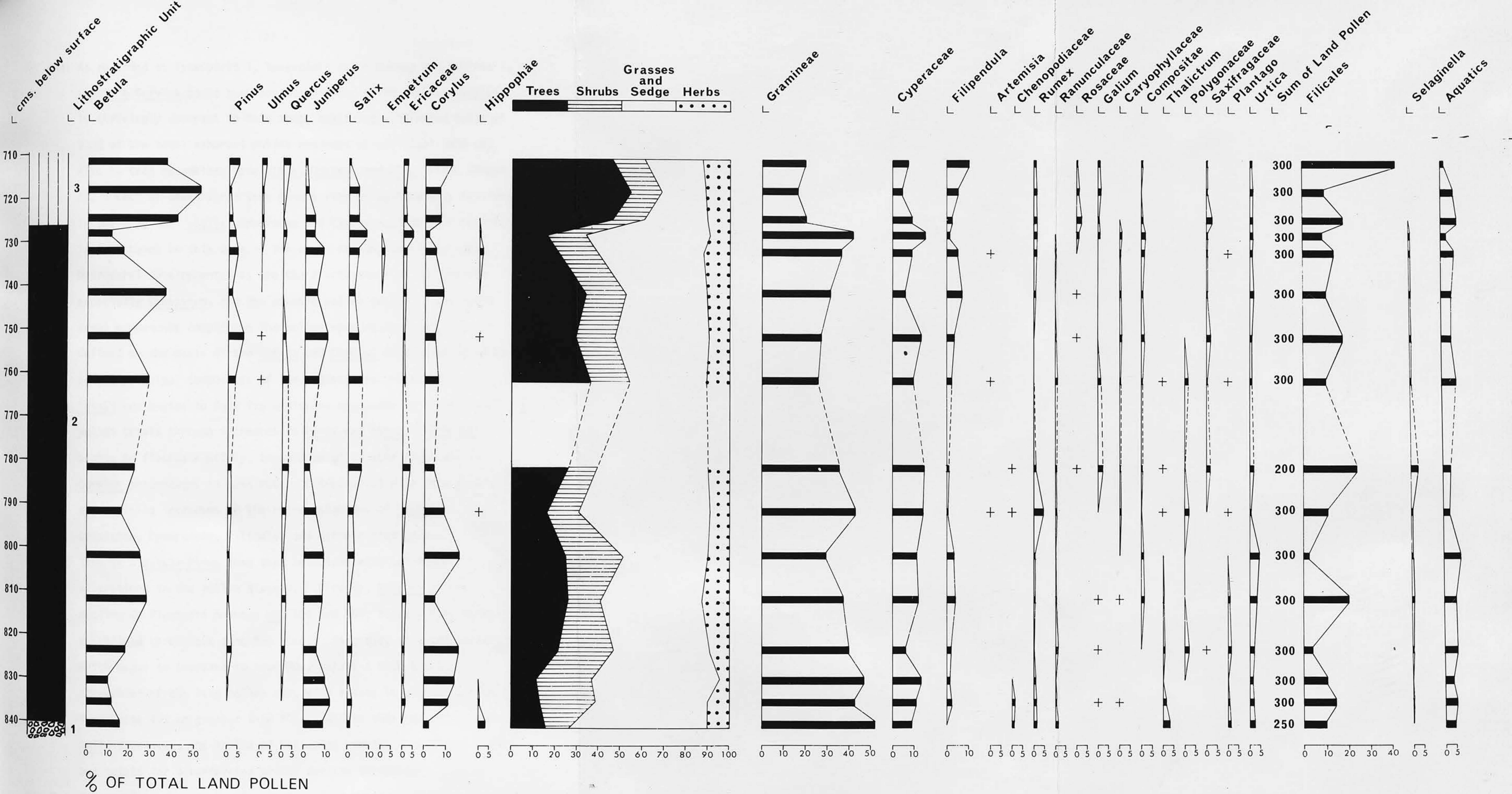


FIGURE 23 MOLLANDS; pollen diagram through basal sediments based on samples collected by small Hiller.

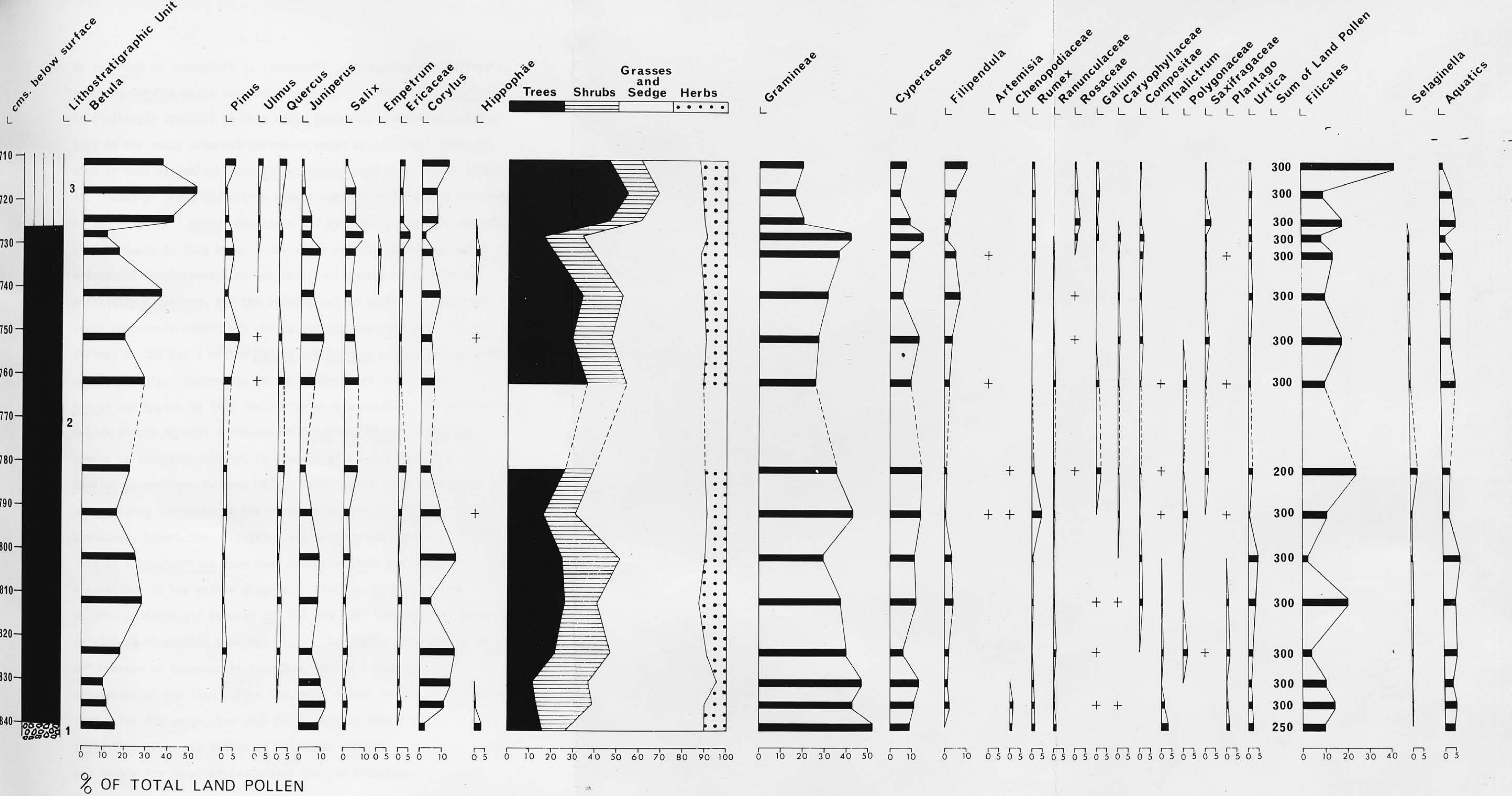


FIGURE 23 MOLLANDS; pollen diagram through basal sediments based on samples collected by small Hiller.

Mod: As recorded at Tynaspirit 1, Tynaspirit 2, Cambusbeg and Amulree 1, a Betula-Corylus phase succeeds the pioneer birch phase. Corylus is strikingly dominant in this zone, achieving a relative value of 533% of the total arboreal pollen recorded at one level (475 cm). Also in this assemblage zone Ulmus, Quercus and Alnus first exceed 5%. Each of these three tree genera remains continuously recorded in the diagram. Salix, Gramineae and Cyperaceae increase markedly in importance in this zone. These are related mainly to local hydroseral developments, as are the fluctuations of the spores, especially Equisetum, and the aquatic pollen grains. The hydroseral components complicate the pollen spectra, but zone Mod is defined on the basis of the Betula and Corylus curves, believed to be the principal components of the regional pollen influx.

Moe: Betula now begins to lose its exclusive dominance in the arboreal pollen totals through increases in Pinus and Alnus. Corylus begins to fluctuate wildly, in advance of a major reduction in Corylus percentages in zone Mof. Coincidental with this phase are striking increases in the representations of Salix, Gramineae, Cyperaceae, Filicales and deteriorated grains.

Mof: This is a Betula-Pinus zone that coincides with two major alterations in the pollen diagram. Firstly, Corylus values decline to fluctuate between ca. 10% and 15%, these values being maintained throughout zone Mog also. Secondly, arboreal pollen, which began to increase in zone Moe, assume a much greater proportion of the land pollen sum, with values in general increasing from below 40% to greater than 60%. Within this zone Alnus and Salix fluctuate, the influx of Filicales remains exceedingly high, but totals for deteriorated grains decline throughout.

Mog: The trend towards increasing dominance of the diagram by arboreal pollen is continued into Mog where values between 60% and 75% are recorded. Alnus accounts for over 50% of the arboreal pollen totals. Quercus, with a maximum value of about 30%, and Ulmus, with a similar maximum value, are at their highest levels in the diagram, whereas Pinus almost disappears towards the upper limit of this zone. Betula totals are consistently lower than in any other zone (15% or less). Also of note in zone Mog are the sharp increases in the curves for Filipendula and Polypodium towards the upper part of the zone, together with increases in the number of deteriorated pollen grains.

Moh: Although Alnus maintains its importance in the pollen diagram, this zone is delimited on the basis of the re-emergence of Betula (to values in excess of 50%) and Corylus (to values greater than 60%). Pinus and Ulmus almost disappear in Moh, and Quercus values are reduced to half the values recorded in zone Mog (to about 15%). The emergence of Corylus is accompanied by marked increases of Ericales, Gramineae, and Sphagnum spores. Salix almost disappears from the total assemblage, and totals for Filicales and deteriorated pollen grains are much reduced.

C. Cores obtained by Abbey piston corer (Fig. 25)

A third and final field investigation at Mollands involved the use of an enlarged piston corer, principally employed for the collection of material from the lowermost organic deposits for radiocarbon assay. In marked contrast to earlier investigations the task of sampling the basal minerogenic deposits was both much easier and more straightforward. Much greater detail of lithostratigraphic variation was observed (see Fig. 12 and discussion in chapter 2). The minerogenic deposits that prevented the passage of the large Hiller were easily penetrated by the Abbey sampler. The sediment record is of a gradual but complex transition from coarse minerogenic to fine minerogenic sediments, then to gyttja deposits, and finally to peat.

The basal minerogenic deposits at Mollands were found to be extremely poor in pollen. Several methods employing treatment by hydrofluoric acid were tested (see chapter 3), but significant pollen numbers were obtained only from about 729 cm upwards. Above this level other layers within the minerogenic sediments were also found to be devoid of pollen. Thus there are no palynological analyses available from the sediments between 729 cm and 845 cm (Fig. 12). The pollen content increases rapidly with the onset of gyttja deposition (716 cm), but the content continues to vary as the sediments vary between gyttja, clay and peat layers.

As with the treatment of the Livingstone cores (chapter 2), disturbance or contamination of the samples is easily detected after bisection of the cores, and samples for pollen analysis and radiocarbon dating were taken from the middle undisturbed parts of the cores. Figures 25a-c present the results of pollen analysis and radiocarbon dating. The close sampling for these diagrams permits a more detailed inspection of the zone Mob of Fig. 24, and the diagrams are divided into two major pollen assemblage zones and a number of sub-zones:-

CORE 7:

Moa: This initial pollen assemblage zone reflects an open herbaceous or dwarf-shrub community, where a variety of herbaceous genera, together with Salix and Empetrum, vary in importance. This zone has been further divided into the following three sub-zones:-

sub-zone I: This is a predominantly herbaceous assemblage sub-zone.

sub-zone II: The herbaceous spectra give way to a Salix-Empetrum-Rumex phase.

sub-zone III: This is an Empetrum-dominated sub-zone in which Empetrum accounts for between 21% and 25% of the total land pollen.

Mob: This zone is equivalent to zone Mob of Fig. 24, a Juniperus-Betula zone where Filipendula is also significant. The more detailed analysis of Fig. 25b enables the subdivision of this zone into four sub-zones:-

sub-zone I: This is an _Empetrum-Juniperus_ phase, a transition phase in which _Empetrum_ values are declining and _Juniperus_ values sharply increase.

sub-zone II: This is a _Juniperus_ sub-zone. _Juniperus_ completely dominates the pollen spectra, at some levels accounting for over 80% of total land pollen. So many _Juniperus_ grains were present at some levels that a scanning technique was employed in order to achieve significant total land pollen counts. All pollen grains were counted until a total of 20 land pollen other than _Juniperus_ was recorded. Juniper grains were then ignored and scanning at the 100X magnification speeded the counting procedure. The number of juniper grains for the final count was extrapolated from the ratio of _Juniperus_ grains to other land pollen grains established for the smaller count at the higher magnification. In order to follow the trends of taxa without the effects of _Juniperus_ over-representation, Fig. 25c was constructed omitting the _Juniperus_ representation for sub-zones Mob I and II and part of sub-zone III. This figure is discussed below.

Sub-zone Mob II has been radiocarbon-dated to 10,670 ± 85 B.P. (HV 5647).

sub-zone III: The _Juniperus_ sub-zone (II) gives way to a _Juniperus-Betula_ sub-zone. _Juniperus_ now maintains much reduced but consistent values at around 20%-25% of total land pollen, and _Betula_, which has been gradually increasing in importance throughout the diagram, records values of between 20% and 30%.

This sub-zone has been radiocarbon-dated to 10,480 ± 150 B.P. (HV 5646).

sub-zone IV: This is a _Betula-Juniperus-Filipendula_ sub-zone. _Betula_ continues to increase to a maximum of 45%, while _Juniperus_ continues to decline to a value of 14%. This sub-zone differs little from sub-zone III, with the exception of the increasing importance of _Filipendula._

CORE 1:

This core contained the gyttja/peat transition at its base, and the top of the core, 654 cm below surface, consisted of the uppermost organic deposits sampled at Mollands using the piston corer. The diagram for this core (Fig. 25a) has been divided into two pollen assemblage zones that are directly comparable with zones in Figs. 24 and 25b.

Mob: This _Betula-Juniperus_ zone is delimited on the same basis as that for Fig. 24, the upper limit being defined by the level at which _Juniperus_ falls below 5% of total arboreal pollen.

Moc: This is a Betula-dominated zone, similar to that identified in Fig. 24. However, there is an important contrast in that this is the only zone in which Corylus appears consistently in those samples collected by piston sampler. It is recorded at values of less than 1% at only two other levels in Fig. 25a. The upper limit of this zone has been radiocarbon-dated to 9,365 ± 120 B.P. (HV 5645).

Discussion

An important comparison can be made between the records of Corylus in each of the Mollands diagrams. In Fig. 23 it appears throughout the minerogenic deposits at percentages varying between 2% and 13%, and usually greater than 5%. In zone Mob of Fig. 24 it is consistently recorded at about 5% throughout. However, in those samples collected by enlarged piston corer not one single grain is recorded throughout the whole sequence of minerogenic and gyttja layers, and in the higher peat deposits significant records of Corylus commence in zone Moc. It must be concluded that severe contamination of the minerogenic deposits has resulted from the use of the small Hiller (Fig. 23), and some noticeable contamination also resulted from using the large Hiller (Fig. 24). Figure 23 is merely presented here as evidence of the amount of contamination that can take place. Severe distortion of other curves in this diagram is also evident when one compares, for example, the curves for Juniperus, Empetrum and Rumex in Fig. 23 with those of Fig. 25b. Figure 23 has not been sub-divided and will not be used in subsequent chapters in discussions of regional pollen assemblage zones or of regional vegetational history.

In Fig. 25 there appears to be some correspondence between some of the biostratigraphic and lithostratigraphic boundaries. Thus the bio-stratigraphic boundary MoaI/MoaII coincides with the lithostratigraphic 2/3 transition (core 7). In other words, the significant increase in the representation of pollen of dwarf-shrubs that characterises sub-zone MoaII coincides with a transition from clay-gyttja laminated deposits to gyttja-peat laminations. Also the Moa/Mob zone boundary roughly corresponds with the transition from laminated deposits to non-laminated organic deposits, and the lower boundary of the dominant juniper phase (sub-zone MobII) coincides with the transition to peaty-gyttja deposition (lithostratigraphic boundary 5/6). However, some of the biostratigraphic boundaries are delimited at horizons where there are no noticeable changes in lithostratigraphy (e.g. MoaII/MoaIII; MobII/MobIII), and conversely some lithostratigraphic changes occur without any corresponding major changes in biostratigraphy (e.g. lithostratigraphic boundaries 1/2 and 6/7, core 7, and 1/2, core 1). The relationship between biostratigraphic and lithostratigraphic boundaries is discussed in chapter 5.

Figure 25c, a total land pollen diagram excluding Juniperus pollen, simply confirms that the trends established in sub-zone MobI are continued throughout sub-zone MobII into sub-zone MobIII without any major alterations. Thus the Betula percentages continue to increase throughout, while percentage values for Empetrum, Gramineae, Cyperaceae and Rumex continue to decline. The marked but artificial reduction of all taxa resulting from the excessively high Juniperus influx recorded in Fig. 25c emphasises, with an extreme example, the effects of over-representation of one or more genera in a relative pollen frequency diagram.

A further point of interest in Fig. 25b is the Pinus curve which includes anomalous peaks at 26% and 17% in sub-zone I of zone Moa. These high percentages can hardly reflect growth of pine in the local area at a time when a pioneer herbaceous and shrub community was developing. Nor can the high Pinus representation have been caused by contamination by pollen brought down into contact with the minerogenic and basal organic deposits by the sampler. Quite apart from the fact that Pinus is only a major assemblage component in zone Mof (240 cm - 350 cm, Fig. 24), if contamination had occurred in this way then one would have expected similar contamination by, for instance, Corylus pollen, which is more abundant by far in the pollen totals. These incongruous Pinus fluctuations are thus attributed to the effects of long-distance transfer and over-representation of this influx due to a very low pollen influx from local taxa. The low local pollen influx in the basal sediments at Mollands has been described above, and the effects of this factor in pollen diagrams from sub-Arctic regions has been discussed by Nichols (1970).

Some general comparisons can be made between the local pollen assemblage zones defined at Mollands and the assemblage zones of other diagrams described in this chapter. Thus the Betula-Juniperus zone (Mob) resembles C1f (Fig. 18), T1e (Fig. 15), T2f (Fig. 17) and Am1f (Fig. 21); the Betula-dominated phase (Moc) is directly comparable to zones C1g, T1f and T2g; and the important Betula-Corylus phase is clearly marked in four diagrams, viz. at Mod, T1g, C1h, and Am1g. The sudden increase in deteriorated pollen grains at the close of the Betula-Corylus zone is coincident with, and as marked as, the sharp decline in Corylus at each site. Later vegetational developments are fully recorded in only two diagrams, those of Mollands and Cambusbeg 1. Although the pattern of declining Betula and Corylus and the development of a dominant Alnus phase (zones Mog and C1j) are similar at both sites, comparisons are complicated by the varying importance of local pollen production at each site, especially of pollen derived from taxa associated with local hydroseral sequences. Thus there is some difference in the totals for Pinus and Ulmus at each site, and in the roles of Salix, aquatic pollen, herbaceous pollen totals, Filicales and other spores, which must reflect differences in local characteristics of pollen influx. This is discussed fully in chapters 5 and 11.

8. GLENTURRET (Fig. 26).

This is the only site at which field investigations of basins within the hummocky moraine delimited by Thompson (1972) resulted in the discovery of a significant depth of sediments. At the deepest point of this relatively small basin over 650 cm of organic deposits were recorded (see chapter 2). About 12 cm of gravelly clay were encountered at the base of the basin, but these deposits were devoid of pollen. Figure 26 presents the pollen spectra from Glenturret based on an arboreal pollen sum of 150. The following local pollen assemblage zones were identified:-

Gla: This is a Betula-Corylus zone where Betula maintains values of about 90% of the total arboreal pollen, and Corylus often achieves totals in excess of 100% of the arboreal sum. Corylus totals are highest (up to 111%) in the lowermost samples, but there is a significant fluctuation in the Corylus curve. Curves for the pollen of Corylus behave in an extremely variable manner in most pollen diagrams from the British Isles, usually attributed to the probability that the hazel shrub was a natural seral element and quickly shifted its areas of relative abundance (Godwin, 1956). However, there is an unusual consistency in the decrease and increase of hazel pollen over 8 levels in Gla, and, because of this regularity in the hazel fluctuation in this instance, it is regarded as more than a mere chance statistical occurrence. Ideally a closer sampling interval is required to support this conclusion. Nevertheless, zone Gla is tentatively divided into three sub-zones:

sub-zone GlaI: a Corylus-Betula-Empetrum sub-zone, with Corylus recording the highest values;

sub-zone GlaII: a Betula-Salix-Corylus sub-zone, with birch recording the highest values and hazel very much reduced;

sub-zone GlaIII: a Corylus-Betula-Salix sub-zone with hazel again dominant in the pollen diagram.

Glb: Both Betula and Corylus decrease throughout this zone. There are marked increases in Ulmus and Quercus, and also of Pinus in the upper part of the zone. The total arboreal and shrub components decrease throughout the zone (see generalised pollen diagram, Fig. 26), but there are major increases in the percentages of Cyperaceae pollen and pteridophyte spores.

Glc: For the first time Betula decreases to below 50% of the arboreal pollen sum in this zone, principally due to sharp increases in the curves for Pinus and Alnus. Corylus records its smallest values in the diagram in this zone. There is a further marked increase in the number of pteridophyte spores which follows the virtual disappearance of aquatic pollen from the diagram. The deteriorated pollen curve also increases markedly here.

Gld: There is an expansion of Corylus once more in this zone. The most characteristic feature of Gld, however, is the prominent peak in the Salix pollen curve. Salix percentages reach 268% of the total arboreal pollen.

Gle: Following the expansion of Corylus in Gld there is a further expansion of Betula in Gle. This coincides with a significant increase in Alnus percentages and with a consistent reduction in the representation of Pinus in the pollen diagram. Salix decreases to very low values, but herbaceous pollen totals are now very much greater.

Discussion

The Betula-Juniperus and Betula-dominated phases that characteristically precede the Betula-Corylus phases at Mollands, Tynaspirit, Cambusbeg, and Amulree, are absent from Glenturret. Comparisons with Mollands are most important, since the beginning of sediment and pollen accumulation at both sites is assumed to post-date the Loch Lomond Stadial. Clearly sediment accumulation and associated pollen deposition began much later at Glenturret than at Mollands. This has important implications for dating purposes and attempts to establish past environmental conditions (see chapter 5, section 4, and Appendix 4).

The Betula-Corylus phase (Gla) resembles that defined at other sites (see above). However, in addition to the more detailed subdivision of Gla, there is an important point of contrast between the Glenturret diagram and the other diagrams. Whereas at Mollands, Tynaspirit 1, Cambusbeg and Amulree 1 the curve for deteriorated pollen grains characteristically increases sharply with the decline of Corylus at the end of the Betula-Corylus phase, this feature is much delayed at Glenturret.

A further point of comparison is that the Corylus totals during the Betula-Corylus phase, like those at Amulree, do not approach the values achieved at any of the sites in the Teith Valley. However, the strongest consistent representation of Ulmus is found at Glenturret, where it suddenly rises to 20% during the Betula-Corylus phase and fluctuates between 10% and 15% throughout the remainder of the diagram.

9. RADIOCARBON DATING (Table 2)

The radiocarbon dates presented above for Tynaspirit 2, Amulree 2 and Mollands are all based on bulked samples, involving the combination of material from four cores, each core being at least 5 cm in diameter. In sampling four bores were put down at the corners of a 30-cm square described on the surface of the bog at each site. Stratigraphic variation over a distance of 30 cm, though noticeable (see chapter 2), was not found to be a major problem, and a minimum distance of 30 cm between adjacent cores was necessary to avoid disturbance of sediments required for subsequent samples.

Combining material from four cores using an enlarged piston corer has enabled dates to be obtained on relatively thin sediment slices (see Table 2), a factor that is critical in the interpretation of radiocarbon dates (see chapter 10). Dates based on bulked samples are often viewed with suspicion, but the procedure used for the dates presented in this thesis is felt to be reliable for the following reasons:

(a) Several of the dates relate to clearly-recognisable lithostratigraphic horizons, where the lithostratigraphic sequence was found to be

TABLE 2 Radiocarbon dates from Tynaspirit 2, Amulree 2, and Mollands

SITE REFERENCE	LABORATORY REFERENCE	MATERIAL	WEIGHT (gm)	SEDIMENT THICKNESS (cm)	$\delta^{13}C$ (‰)	DATE (Radiocarbon years B.P.)
(a) Tynaspirit 2						
TY-370	HV-4984	Humified peat with small wood fragments	165.0	2.0	*	9,260 ± 100
TY-404	HV-4985	Fine-detritus peat, plus clay	218.0	2.5	*	10,420 ± 160
TY-423	HV-4987	Gyttja	201.0	2.0	*	11,385 ± 290
TY-430	HV-4988	Fine-detritus peat	148.0	2.0	*	12,395 ± 195
TY-435	HV-4989	Gyttja	199.0	2.0	*	12,750 ± 120
(b) Amulree 2						
AM-872	HV-5642	Fine-detritus peat	113.5	1.5	-29.6	9,115 ± 120
AM-890	HV-5643	Fine-detritus peat	153.2	2.0	-25.7	10,270 ± 100
AM-900	HV-5644	Gyttja/fine-detritus peat	161.0	2.0	-31.8	10,770 ± 90
(c) Mollands						
MO-660	HV-5645	Fine-detritus peat	116.4	1.5	-32.0	9,365 ± 120
MO-696	HV-5646	Fine-detritus peat	103.1	1.5	-29.5	10,480 ± 150
MO-700	HV-5647	Gyttja	248.1	2.0	-28.3	10,670 ± 85

* Not corrected for $\delta^{13}C$

consistent in all four cores at each site. The exceptions to this constraint are TY-370, TY-430, AM-872, AM-890, MO-660 and MO-696.

(b) At Tynaspirit and Amulree the full sequence of dated sediments was obtained in a single chamber in each bore.

(c) In the laboratory the cores were cut into slices of 2-3 cm, and the outer 0.5 cm of those slices used for dating was automatically discarded. The remaining portions of these slices were inspected for any signs of contamination, due to sediment distortion or sediment transfer from one level to another. No sign of contamination was found in any of the samples used for radiocarbon dating.

(d) For samples TY-370, TY-430, AM-872, AM-890, MO-660 and MO-696 estimates of the critical horizons (see Table 3) are based on measurements from clearly-recognisable lithostratigraphic horizons. Since the lithostratigraphic units identified at each site were found to vary in thickness only very slightly, this is considered to be a fairly reliable procedure for these particular sites.

Table 2 gives the thickness, type and weight of material used for each radiocarbon determination. The constraints employed in identifying the critical horizons combined for each assay are given in Table 3. There is the possibility that for those samples based on subjective estimates of the critical horizons the exact biostratigraphic horizons may not have been correctly identified in all of the cores. For reasons given above, however, this is not thought to affect the radiocarbon dates greatly.

All of the radiocarbon dates were measured at the Niedersächsisches Landesamt für Bodenforschung, Hanover. In each case the weight of material supplied for dating (Table 2) was greater than that required for an adequate gas sample to be prepared for analysis, and this is reflected in the relatively small standard deviations associated with the majority of the dates. Of those dates for which $\delta C13_{PDB}$ values are available (Table 2), two of these (MO-660 and AM-900) lie outside the normal range of $\delta C13$ values observed for wood, peat, gyttja and charcoal from European

TABLE 3: Constraints in the identification of critical horizons in individual cores to be bulked for radiocarbon dating

SITE REFERENCE	LABORATORY REFERENCE	Identification of critical horizon
(a) Tynaspirit 2 (see Fig. 17)		
TY-370	HV-4984	Estimate based on measurement from l.b. 10/11.
TY-404	HV-4985	Thin clay horizon of l.u. 10 clearly visible in each core (see also Fig. 10).
TY-423	HV-4987	Lowest 2 cm of gyttja of l.u. 6.
TY-430	HV-4988	Estimate based on thickness of l.u. 5 measurement from l.b. 4/5.
TY-435	HV-4989	Lowest 2 cm of gyttja of l.u. 4
(b) Amulree 2 (see Fig. 22)		
AM-872	HV-5642	Estimate based on measurement from l.b. 1/2 (c.f. core 20).
AM-890	HV-5643	Estimate based on measurement from l.b. 1/2 (c.f. core 20).
AM-900	HV-5644	Lowest 2 cm of gyttja/fine-detritus peat (c.f. l.u. 2, core 20, l.u. 6, core 18).
(c) Mollands (see Fig. 25)		
MO-660	HV-5645	Estimate based on measurement from upper horizon of gyttja deposits (c.f. l.b. 1/2, core 1, l.b. 6/7, core 7).
MO-696	HV-5646	As for sample MO-660.
MO-700	HV-5647	Lowest 2 cm of gyttja/peaty-gyttja (c.f. l.u. 5 and base of l.u. 6, core 7).

l.u. = lithostratigraphic unit
l.b. = lithostratigraphic boundary

localities, i.e. $\delta C13_{PDB} = -25 \pm 5^{o}/oo$ (Oeschger et al., 1970). A further two samples (AM-872 and MO-696) have $\delta C13_{PDB}$ values that lie close to the limits of the normal range. No $\delta C13$ values are available for the dates from Tynaspirit. These $\delta C13$ values may infer that correction for fractionation is required, but whether or not the appropriate correction values would be significant in terms of the ranges of the standard deviations associated with these dates must await the availability of reliable correction factors for $\delta C13_{PDB}$ values related specifically to the types of biogenic material contributing to the organic deposits (R.E.G. Williams, personal communication).

10. CONCLUSIONS

Local pollen assemblage zones have been defined for each of the pollen diagrams and these have been designated by numerals or letters. Before comparisons are made with other sites in northern Britain it is necessary to establish the total time period covered by the diagrams collectively, and to establish the probable time-stratigraphic relationships between the diagrams. As a framework for comparisons it is necessary to designate the pollen zones by names, based on the recognition of the major regional components, and to establish the more widespread regional pollen zones for southern Perthshire, again designated by name. The advantages of named pollen zones has been discussed by Birks (1973).

As shown in this chapter, there are a number of basic similarities between the various pollen diagrams. The extent to which these similarities can be regarded as time-equivalent is complicated by a number of complex variables that affect several, if not all, of the pollen diagrams. These include contamination, lithostratigraphic and biostratigraphic distortion, the effects of long-distance transfer, and local over- and under-representation of taxa, especially in relation to the variable importance of the local hydroseral taxa as sources of local pollen influx. These factors affect the correlation and interpretation of the local pollen assemblage zones and assessments of the validity of the various radiocarbon dates. Their influence in the pollen diagrams is therefore discussed in chapter 5 prior to the correlation of local pollen assemblage zones in chapter 7.

CHAPTER 5

Problems in lithostratigraphic and biostratigraphic interpretation with special reference to Lateglacial and early Flandrian deposits

1. INTRODUCTION

Some of the problems encountered in lithostratigraphic and biostratigraphic interpretations of pollen profiles have been briefly described in previous chapters. This chapter deals with specific problems in more detail and attempts to indicate some of the more severe problems that may generally be encountered in pollen analysis of Lateglacial and early Flandrian deposits. Synthesis of the evidence provided by the pollen diagrams in the correlation of local pollen assemblage zones (chapter 7) must be preceded by consideration of the various stratigraphical problems and the variable effect of each on individual pollen diagrams.

A crucial factor in this thesis is the relationship of the pollen diagrams to the Loch Lomond Stadial ice-limits proposed by Thompson (1972) for southern Perthshire (chapter 2). This requires discussion firstly of the confidence with which Lateglacial zones can be delimited, and secondly of the extent to which fluctuations in the pollen curves reflect climatic and other environmental changes. The problem of delimiting Lateglacial zones is most apparent in the analysis of the Amulree pollen diagrams.

It is recognised that the absence of a basal biostratigraphic sequence does not necessarily imply that a particular site was ice-covered during the Loch Lomond Stadial. The basal biostratigraphic zone at any site may not indicate the true age of formation or deglaciation of that particular basin, for there may be some delay between formation or deglaciation and the onset of sedimentation. This problem is most apparent in the discussion of the Glenturret pollen diagram.

In order to define regional pollen zones from a number of pollen profiles it is necessary to assess the possible degree of distortion of the representation of regional vegetation in the pollen spectra of the various lithostratigraphic and biostratigraphic units. There are three basic modes of distortion, though there is a number of complicated variables within each:

(a) the degree of non-continuous or disturbed sedimentation;
(b) the amount of over-representation of the pollen of local taxa, and of under-representation of regional taxa in the pollen spectra;
(c) the possibility of re-deposition, deterioration, or even complete destruction of pollen grains through time, both in terms of complete pollen assemblages, and in terms of an individual taxon.

As far as can be ascertained there are no signs of serious stratigraphic disturbance or of interruption of sedimentation in any of the sedimentary sequences on which the pollen diagrams in this thesis are based. There is no lithological evidence for disturbance, and the conclusion that no serious stratigraphical disturbance or non-continuous sedimentation occurs is supported by the biostratigraphic data in two ways:

(i) the logical progression of the pollen curves in individual diagrams, and the gradual, seldom abrupt, changes within individual pollen curves for the regional taxa (see chapter 4);
(ii) the good degree of comparison in vegetational development between the various sites (see chapter 7).

It is difficult to estimate the likelihood of stratigraphic disturbance when referring to minerogenic deposits, as in the basal deposits of Cambusbeg, Tynaspirit, Amulree and Mollands. Nevertheless, in the absence of evidence to the contrary, and on the basis of the apparently undisturbed nature of the polleniferous deposits, it is assumed that disturbed or non-continuous sedimentation are not serious problems in the pollen profiles presented in this thesis.

Other stratigraphic problems do, however, exist. In order to assess these constraints use has been made of close-sampling, analysis of deteriorated pollen (chapter 6), and radiocarbon-dating where possible. The reliability of the radiocarbon dates is much affected by the possibility of re-sedimentation, deterioration, and contamination, and the dates are thus discussed in comparisons of the local pollen assemblage zones (chapters 7, 8 and 9).

2. THE LATEGLACIAL LITHOSTRATIGRAPHIC SEQUENCE

In most basins in Scotland where sediments of Lateglacial age have been studied the infill consists of a considerable thickness of Flandrian peats and lake muds underlain by a three-fold sequence of minerogenic-organic-minerogenic sediments (Sissons et al., 1973). This lithostratigraphic sequence has in the past been equated with the Jessen-Godwin pollen Zones I, II, and III (see chapter 1). Donner (1957) first demonstrated the relationship of basin deposits to Lateglacial ice-limits in Scotland. However, he had to rely on lithostratigraphic definitions since he was unable to obtain pollen from the minerogenic deposits of the Lateglacial sequence. Donner maintained that sites that lie outside the Loch Lomond Readvance ice limits should contain a basal three-fold Lateglacial lithostratigraphic sequence. Tynaspirit 1, Tynaspirit 2, Cambusbeg and Amulree all lie outside the Loch Lomond Stadial ice-limits of southern Perthshire (Fig. 5) and yet a three-fold sedimentary sequence is only to be found in the Tynaspirit basins.

At Tynaspirit 1 (Fig. 15) 20 cm of highly organic deposits separate two layers of grey compact clay, and at Tynaspirit 2 (Fig. 17) 15 cm of peat also separate two clay layers. The clear biostratigraphic records from both of these basins, and the radiocarbon dates from Tynaspirit 2 (chapter 4), confirm a Lateglacial interpretation for this sequence. Tynaspirit is thus the key site for the interpretation of Lateglacial sediments in this area.

By contrast, a three-fold sedimentary sequence is absent at Cambusbeg and Amulree. At Cambusbeg a very soft grey clay was found between 1095 and 1140 cm (lithostratigraphic unit 3, Fig. 18). Some of these clay samples were of a brownish-grey hue, but closer inspection in the laboratory revealed that this brown colouration was not consistent throughout the samples but formed a brownish film on the outside of the samples. This therefore indicates contamination as a result of using the Hiller borer (see appendix 2). Although great care was taken to avoid using clay samples with brown staining in the preparation of slides for pollen analysis, contamination of the clay deposits is confirmed by comparisons of the pollen records of Cambusbeg and Tynaspirit 1 and Tynaspirit 2 (chapter 4).

The pollen record for the basal 45 cm of minerogenic deposits at Cambusbeg is interpreted as providing evidence for a Lateglacial vegetational sequence. It was immediately assumed that preliminary investigations at Cambusbeg had failed to discover the deepest part of the basin. However, a number of test-bores were later made at Cambusbeg with attention focused on the deeper parts of the basin, yet no evidence was found for a basal three-fold sedimentary sequence. It is possible that the use of more sophisticated equipment and laboratory procedures might reveal some slight variation in organic content of the sediments, or perhaps reveal the presence of a very thin organic-rich layer that has previously been disturbed by the augering mechanism of the Hiller chamber. Attempts to sample the basal deposits using a Russian peat corer, a Dachnowski piston corer and an Abbey piston corer all failed since the soft deposits were not retained in the respective chambers. More successful sampling might result from the use of equipment that freezes the fluid deposits prior to extraction.

The contrast between the basal sediments at Cambusbeg and those in both Tynaspirit basins is thus problematic. Stratigraphic interruption, delay in the onset of sedimentation, and the possibility that Loch Lomond Stadial deposits are too coarse to allow penetration to earlier deposits could all be advanced as explanations for the absence of a fuller litho-stratigraphic sequence at Cambusbeg. On the other hand, the pollen record indicates a comparable vegetational sequence to that of the Lateglacial deposits at Tynaspirit (chapter 4).

There is also considerable contrast in the nature of the Flandrian deposits at the Cambusbeg and Tynaspirit sites. In both Tynaspirit basins the Flandrian deposits are composed of a dry, compact peat rich in plant detritus. The Flandrian sediments at Cambusbeg consist of an extremely soft, homogeneous, organic-rich mud which is watery in nature between 870 and 950 cm and gel-like between 950 and 1070 cm (Fig. 19). The latter deposit has been termed dy (Faegri and Iversen, 1964). Between 150 and 870 cm an extremely watery organic mud, or in some places only water, is enclosed by a floating mat of mire vegetation supporting a number of birch trees. This basin thus corresponds to the "schwingmoore" (Moore and Bellamy, 1974).

The reason for the marked differences in the basal sediments in these basins that are only 2 km apart may lie in the variation in depth, morphology and catchment at each of these sites. Cambusbeg is 11.4 m deep, whereas Tynaspirit 1 is 6.5 m deep and Tynaspirit 2 only 4.4 m deep. Cambusbeg also has a shallow rim around the edge of the basin, from which samples of peat were obtained in a number of cores. The basin deepens quite rapidly from this rim. The Tynaspirit basins have fairly constant gentle slopes from the edges to their centres. It appears that marginal macrophytic vegetation has been confined to the shallow edge of the Cambusbeg basin, even in late Flandrian times, and that little organic detritus has been carried into the deeper part of the basin. Since this is true for the Flandrian deposits it may also have applied in Lateglacial times. At a time when vegetational cover on the slopes surrounding the basin may have been incomplete, the absence of a significant layer of organic detritus in the deeper part of the basin would not be surprising. A further possibility is that the lake waters at Cambusbeg were extremely oligotrophic by comparison to the lake waters at Tynaspirit. In such situations very poor assemblages of floating mat macrophytic vegetation develop, often dominated by a single species, and dystrophic or gelatinous muds develop rather than richly fossiliferous peats (Moore and Bellamy, 1974). A marked difference in trophic conditions between Cambusbeg and Tynaspirit would be difficult to explain as there is no major difference in the geology of the catchments. Both basins occur within mounds of sands and gravel. However, there is a much more open catchment at Tynaspirit, with streams leading directly off the higher slopes to the north, while the Cambusbeg basin is more isolated amidst sand and gravel mounds.

In contrast to Cambusbeg, where a more detailed inspection of the basal sediments has not yet been possible, there is more intricate evidence available for the basal deposits at Amulree. Preliminary sampling at this site revealed 12.0 m of deposits at the deepest point, with the lowest 3.75 m composed of clay. The clay varied in consistency and colour, but there was no indication of a significant development of an organic component. A basal three-fold sedimentary sequence is absent at Amulree. Pollen diagram Amulree 1 records Corylus pollen throughout the clay deposits and below the main Juniperus peak in the diagram (zone Am1f, Fig. 20). This is in conflict with the Tynaspirit 2 diagram and indicates that the basal clays at Amulree 1 have been contaminated during sampling.

Reinvestigations at Amulree, using an Abbey piston corer, provided very clear and detailed stratigraphic data (chapter 2). Sampling was impossible below a depth of 1075 cm, but the cores collected were sufficiently deep to include the Lateglacial Interstadial amelioration phase recorded in Amulree 1 (zone Am1c). The Amulree 2 cores showed little signs of distortion, and Corylus was represented at only 2 levels below the Juniperus peak (zone Am2g) with values of less than 1% of total land pollen (Fig. 22).

Use of an enlarged piston sampler at Amulree was possible because the sediments are compact, and this has provided an opportunity for detailed inspection of basal clays, the results of which may also prove valuable for an explanation of the Cambusbeg sediments. In the case of Amulree there is no visible Lateglacial lithostratigraphic sequence that can be compared with the tripartite sequence reported by previous workers (chapter 1), and yet this site lies outside the proposed Loch Lomond Stadial ice-limits (Fig. 7). There are a number of possible explanations as alternatives to a Lateglacial interpretation for the basal clays:-

(a) that the deepest part of the basin has not been located;

(b) that the Loch Lomond Stadial ice-limit is incorrect for this part of the Grampians and that only Flandrian sediments have accumulated in this basin;

(c) that the basin was not covered by ice in the Loch Lomond Stadial but that Interstadial sedimentation was interrupted or delayed.

Point (a) has been discussed in chapter 2 and is discounted. Points (b) and (c) are discounted on the basis that a Lateglacial vegetational sequence is interpreted from the Amulree pollen diagram. However, the pollen record at Amulree is by no means straightforward. The pollen record between 8.0 m and 12.0 m is best compared with the detailed early Flandrian records from Mollands (see chapter 4), for this shows that a much more complex vegetational sequence is recorded in the basal sediments at Amulree than that of the Loch Lomond Stadial/Flandrian transition recorded at Mollands. The _Juniperus_-_Rumex_-_Empetrum_ phase of zone Am2c (Fig. 22) suggests a developing shrub vegetation following a dominantly herbaceous phase (Am2a and Am2b). The herbaceous phase prior to zone Am2c also contains extremely high _Lycopodium_ and _Selaginella_ totals, suggesting open conditions and skeletal and disturbed soils. The increase in _Rumex_ to its highest consistent representation in the diagram (15%-20%), the frequencies of _Juniperus_ and _Empetrum_, and the lowest recorded totals for _Artemisia_ and Caryophyllaceae suggest a closer vegetation cover with a shrub component, indicating more stable soils on local slopes in zone Am2c. The pollen spectra in zone Am2d suggest a return to disturbed soil conditions, with marked reductions in the representations of _Juniperus_, _Empetrum_ and _Rumex_, and the development of communities with _Artemisia_, _Lycopodium_, Caryophyllaceae, Gramineae and Cyperaceae dominant. This overall pattern differs markedly from that obtained from the basal deposits at Mollands (chapters 4 and 7).

A further contrast with the Mollands site exists in the nature of the sediments. At Mollands (Fig. 25) there are alternating coarse and fine sediments reflecting variation in the rate of ice-melt, and this is succeeded by alternating thin bands of minerogenic and organic-rich layers reflecting a gradual transition from disturbed to stabilised soils on surrounding slopes. At Amulree there is variation in the colour of the clays (for more detailed analysis see section 5) but only exceedingly small alternations in grain-size. It might be expected that if the basal 3.75 m of clay at Amulree represent the Loch Lomond Stadial/Flandrian transition phase, then an equally-marked minerogenic-organic transition as that found at Mollands would have developed. Instead of a gradual transition from Loch Lomond Stadial minerogenic sediments to Flandrian peat there is a sharp boundary at Amulree.

There is a suggestion of a sedimentary break at level 964 cm in the Amulree 2 core, where the clay becomes more compact, and there is a sudden absence of pollen between 964 and 957 cm. However, there are no apparent differences in the general trends of the pollen curves above and below these levels. If zone Am2c represents the Lateglacial Interstadial and zone Am2d the Loch Lomond Stadial, then any break in sedimentation is not sufficient as to prevent the recognition of the Lateglacial sequence, and the hypothesis that this site contains Flandrian sediments only cannot be accepted. It could be argued that the amelioration phase Am2c and the revertence phase Am2d represent a minor climatic oscillation within the Loch Lomond Stadial or Loch Lomond Stadial/Flandrian transition periods. Since there is no evidence for an oscillation within the Loch Lomond Stadial/Flandrian transition in the detailed pollen diagram from Mollands, and since there is no evidence as yet for a subdivision of the Loch Lomond Stadial in Scotland, this interpretation is considered unacceptable.

A further point to note is that the 3.75 m of clays at Amulree, containing numerous laminations, implies deposition over a long period of time. An alternative hypothesis is that the clays were deposited rapidly as a result of abundant glacier flour provided by meltwaters from a local glacier terminus. On the basis of Thompson's (1972) Loch Lomond

Readvance ice-limits this would seem unlikely. According to Thompson the only glacier in the immediate vicinity during the Loch Lomond Stadial was the Almond Valley glacier (see Fig. 13), and this terminated south of and at a lower altitude than the watershed of the Girron Burn which flows northwards through the Amulree basin. Meltwaters from the Almond Valley glacier terminus would have had a clear exit south-eastwards through the Sma' Glen, along the present course of the River Almond.

An important conclusion to this section, therefore, is that continuous sedimentation throughout the Lateglacial period need not have resulted in a clear lithostratigraphic sequence, and that minerogenic sedimentation appears to have dominated throughout the Lateglacial Interstadial at certain sites in the Scottish Highlands. In addition to Amulree and Cambusbeg at least four other basins in Scotland have been reported where organic detritus failed to form a separate lithostratigraphic unit in the Interstadial. At Loch Cill Chriosd in southern Skye there was very little accumulation of organic sediments prior to 10,000 B.P. (Birks, 1973). At Loch Sionascaig (Sutherland), although there was a change to a more brownish clayey-silt, Pennington et al. (1972, p.216) reported that "This profile was unique in our experience of lake cores in the absence of abrupt lithological changes ..." and "no late-glacial sediment in any of these lakes has the brown colour given by humic compounds ..." Also at Loch Craggie (Ross and Cromarty) Pennington et al. (op. cit., p.242) found Lateglacial sediments where "... the interstadial sediment was a silty clay with no visible organic content." At Roineach Mhor in Angus a complex sequence of sands, silts and clays, sometimes rhythmically-bedded, is recorded (Walker, 1975a). No organic deposits are recorded from Lateglacial deposits at this site.

The six basins referred to in this section, where organic deposits failed to accumulate during the Lateglacial Interstadial, vary considerably in size, situation, and in other attributes. They indicate that in the Scottish Highlands pollen analysis of basin sediments is essential when relating basin sediments to suggested Loch Lomond Stadial ice-limits. Arguments based on lithostratigraphy alone may be misleading.

3. RELATIONSHIP BETWEEN BIOSTRATIGRAPHIC AND LITHOSTRATIGRAPHIC BOUNDARIES

Donner's early work in the Scottish Highlands (1957, 1958, 1962) inspired further interest in the development of the Scottish Lateglacial environment, but whereas Donner had been forced, by an apparent absence of pollen in clay deposits, to subdivide the Lateglacial on lithostratigraphic criteria alone, later research was fortunately not restricted in this way. Vasari and Vasari (1968, p.10) pointed out that "... contrary to previous suppositions, the Late-glacial clays often contain pollen in sufficient quantities to allow a zonation to be based on pollen criteria alone." Moar (1969a, 1969b) reported that early work for Scotland, Ireland and Wales indicated that, unlike other areas in north-west Europe (including England), pollen boundaries often did not coincide with sedimentary horizons. Moar made careful distinctions between lithostratigraphic and biostratigraphic criteria in his work and subdivided his pollen diagrams solely on biostratigraphic data. This is now standard practice where sufficient pollen can be abstracted from sediments, and the pollen diagrams in this thesis are all subdivided on the basis of biostratigraphic variation.

One major consequence of the separation of lithostratigraphic and biostratigraphic criteria is a recognition of frequent non-correspondence between lithostratigraphic and biostratigraphic boundaries. Examples of this are as follows:-

(a) Tynaspirit 1 (Figs. 15 and 16)

At this site there are marked floristic changes that do not accord with lithological changes. Thus, for instance, pollen zone boundary Tla/Tlb records major changes in floristic composition, yet there is no apparent change in lithology at this level. The change from clay to gyttja (lithostratigraphic unit 2/lithostratigraphic unit 3) does coincide with a major change to pollen assemblages dominated by Betula and Juniperus, but the higher boundary of gyttja to peaty-gyttja does not coincide with a pollen zone boundary. Similarly, the pollen evidence for a marked deterioration in environmental conditions at the Tlc/Tld boundary occurs 8 cm below the sharp boundary between peaty-gyttja and clay (lithostratigraphic units 4/5). A marked Juniperus peak in this diagram (zones Tld-Tle) occurs with no change in lithology, being entirely within the clay deposits of lithostratigraphic unit 5. This contrasts with the Mollands diagram (Fig. 25) described below. The change from clay to peaty-gyttja and finally peat (lithostratigraphic units 5/6) coincides with pollen zone boundary Tle/Tlf.

(b) Mollands (Figs. 24 and 25)

Figure 25 provides an extremely detailed picture of lithological and vegetational variation as a response to the Loch Lomond Stadial/Flandrian transition. Such an analysis thus provides a test of the hypothesis that much of the non-correspondence between lithological and biostratigraphical boundaries may be a result of the lack of detail in analysis, or the result of distortion due to the use of the Hiller peat borer. In this diagram the basal clay and banded clay and gyttja sediments (lithostratigraphic units 1 and 2) correspond to pollen sub-zone Moa I, and the transition to banded gyttja and peat deposits corresponds to a marked floristic change with the expansion of shrubs in sub-zone Moa II. But despite the fact that all lithological and biostratigraphic boundaries are clear and sharp there are no other occasions in the diagram where they coincide. It is more probable that the changes from clay to greenish gyttja, to peaty-gyttja, and finally to peat, reflect variation in the absolute pollen influx rather than changes in the local pollen assemblages. The well-marked change from peaty-gyttja to peat does not coincide with major pollen variations, either in Core 1 or in Core 7.

(c) Amulree (Figs. 20, 21 and 22)

There are problems in analysing the basal sediments at Amulree 1 since there is evidence for much distortion caused by the Hiller boring mechanism. Nevertheless it can be seen that the two most well-marked lithological boundaries (9/10 and 10/11) coincide with major changes in pollen assemblages. The sediments sampled for diagram Amulree 2 (Fig. 22) were not distorted and this permits a more exact comparison of lithostratigraphic and biostratigraphic variation. Only one biostratigraphic boundary here coincides exactly with a lithological boundary, viz. Am2a/Am2b with the change from laminated grey and pink clays to non-laminated faint pink clays (lithostratigraphic units 1/2 - Core 25). No other minerogenic transitions accord with major biostratigraphical transitions. The most marked boundary, the change from grey clay to Flandrian peat, also does not coincide exactly with a biostratigraphic boundary. In Core 20 the transition between lithostratigraphic units 1 and 2 occur 8.0 cm below the pollen zone boundary Am2f/Am2g, and in Core 18 the lithostratigraphic transition 5/6 is 7.0 cm above the Am2e/Am2f boundary. In neither core are there marked pollen assemblage changes at the lithological transition.

The above descriptions do not constitute an exhaustive account of the examples of non-correspondence between lithological and biostratigraphical variation, but are a selection from the Lateglacial profiles. In addition to these, the Glenturret diagram (Fig. 26) demonstrates that there is also non-correspondence between Flandrian peat transitions and major pollen zone boundaries. Since biostratigraphic boundaries are defined in terms of regional vegetational changes (arboreal mainly) there need be no direct relationship between pollen zone boundaries and peat stratigraphy, which is composed almost exclusively of remains of plants that are components of the local seral successions or bog communities. Though regional vegetational changes, even as a result of widespread environmental changes, can occur without major changes in basin deposits, it would be expected that peat stratigraphy would bear a close relationship to local pollen contributors, and especially to those taxa recognised as part of the local hydroseral sequence. In Fig. 26 there is no direct relationship between peat stratigraphy and local pollen assemblages. Thus for instance pollen zone boundary Glb/Glc is defined on regional pollen changes, viz. the increased percentages of Alnus and Pinus and lowest percentages for Corylus in the diagram, but this boundary also coincides with the change from aquatic to marsh-fen conditions. (The final significant representation of aquatic pollen occurs at this boundary.) These transitions occur with no apparent change in peat type.

In contrast to the Lateglacial sediments reviewed above, and with the exception of one pollen zone boundary (the T2b/T2c boundary), there is generally good agreement between lithostratigraphic and biostratigraphic boundaries at Tynaspirit 2 (Fig. 17). The T2a/T2b boundary occurs within gyttja deposits. This gyttja is only 3.5 cm thick and it is thus difficult to obtain detailed analysis of changes within it. The T2c/T2d boundary, which marks the beginning of the Loch Lomond Stadial, coincides with a thin gyttja layer (lithostratigraphic unit 6), a transition from clay to peat (lithostratigraphic units 5 to 7). The T2d/T2e boundary, the upper limit to the Stadial, also coincides with a thin gyttja layer, lithostratigraphic unit 8, which is transitional between the Loch Lomond Stadial clays (7) and Flandrian peat (9). The T2e/T2f boundary coincides with lithostratigraphic unit 10, a thin clay layer.

There is evidence from all of the sites for clear non-correspondence between lithostratigraphic and biostratigraphic boundaries, but also some evidence for direct correspondence. The evidence from sites Cambusbeg 1, Tynaspirit 1, Amulree 1 and Glenturret shows marked non-correspondence, but all of these diagrams are based on samples collected by Hiller borer and this might therefore be explained as distortion of the sediments and contamination by the auger mechanism. This would be particularly severe where the auger was passing through organic deposits rich in pollen and spores into minerogenic deposits that were extremely poor in pollen and spores. In such situations a minimal amount of organic contamination could result in severe distortion of the pollen spectra.

The diagram for Tynaspirit 2 (Fig. 17) provides clear evidence for good correspondence of lithostratigraphic and biostratigraphic boundaries, and since sampling for these cores was by enlarged piston corer this would seem to support the hypothesis that distortion during sampling accounts for much of the non-correspondence in other sites. However, in the diagrams for Amulree 2 (Fig. 22) and Mollands (zone Moa, Fig. 25), equally detailed analyses as a result of using an enlarged piston corer revealed strongly discordant lithostratigraphic and biostratigraphic boundaries. There must be, therefore, some sedimentary or other local variables that cause this discordance, possibly indicating some time-lag between vegetational and sedimentary responses to environmental changes. For instance, the change from clay to organic deposits may reflect a regional transition from disturbed soil conditions to stable soil and vegetation. It is possible, according to local conditions, that floristic changes are recorded immediately in the pollen influx into the deposits before the deposition of minerogenic deposits has entirely ceased. Conversely, a climatic deterioration resulting in the destruction of soils and revertence in vegetational developments may be reflected more immediately in the pollen influx than in lithostratigraphy.

Most of the evidence from the pollen diagrams in this thesis suggests that biostratigraphic changes are more immediate than lithostratigraphic changes. For instance, in Tynaspirit 1 (Figs. 15 and 16) the transition from organic deposition to clay (lithostratigraphic boundary 4/5) occurs 7.0 cm above the palynological boundary for the first indications of major deterioration in the environment (Tlc/Tld). Similarly, the lithological indications for the end of the Loch Lomond Stadial period (5/6) occur 10.0 cm above the pollen zone boundary Tld/Tle that marks a dominant Juniperus peak in the diagram. Presumably there is some time-lag in the build-up of soil after a phase of erosion, when climatic conditions have improved, and conversely there is some delay in the disturbance of soils after the close of a stable period for soils and vegetation.

The degree of non-correspondence between lithostratigraphic and biostratigraphic boundaries, and thus the variation in the response of both to environmental change, is very much dependent on local factors. This can readily be seen in a comparison of the diagrams from the adjacent basins of Tynaspirit 1 (Fig. 15) and Tynaspirit 2 (Fig. 17). In addition Amulree 1 (Fig. 20) shows an almost immediate change from minerogenic to organic sedimentation abruptly after the decline of those plants that indicate disturbed soil conditions, thus marking the close of the Loch Lomond Stadial period (zone Amld). Discordance between lithostratigraphic units and biostratigraphic zones may have some influence on the interpretation and correlation of pollen zones, and along with the effects of deterioration (chapter 6) this is further discussed when correlating Lateglacial pollen assemblage zones (chapter 7).

Changes within minerogenic sediments (for instance in the colour of clays or gyttja deposits), and the transition between minerogenic and organic deposits, will depend not so much on the assemblages of pollen as on the absolute rate of the pollen influx (and of other fine organic particles), for which there are no data available. In addition, changes within peat stratigraphy will depend on a complex number of interdependent local factors rather than on variations in regional vegetation. Thus a close relationship between pollen assemblage zones (based mainly on arboreal pollen variations) and changes in peat stratigraphy is not really to be expected. However, one might reasonably expect a close relationship between peat variations and changes in local vegetational components, such as aquatic, sedge, moss and certain fern and herbaceous taxa that are major contributors to peat accumulation. In a number of instances this does not occur. In the Mollands diagram (Fig. 24) the change from aquatic to marsh-fen conditions (pollen zone boundary Mod/Moe) occurs below the change from compact dark dry peat to Sphagnum peat (lithostratigraphic boundary 3/4). Similarly, a major floristic change occurs at pollen zone boundary Mog/Moh over 30.0 cm below the stratigraphic change from Sphagnum peat to dry compact peat (lithostratigraphic boundary 4/5). On the other hand, in the Amulree 1 pollen diagram (Fig. 21) the change from telmatic to terrestric peat (pollen zone boundary Amlg/Amlh) accords with the stratigraphic change from dry peat to Sphagnum and sedge peat (lithostratigraphic boundary 10/11). The evidence from Glenturret has already been discussed above.

From the above evidence it appears that changes in local floristic composition are not always reflected by peat characteristics, and that often changes in peat composition lag behind major floristic changes. There are a number of possible reasons for this. One major difficulty is that the cores analysed in this thesis have been taken from the deepest parts of the basins, and the continued presence of water and associated shallow-water macrophytic vegetation may be masked by the local over-representation of the microfossils of the terrestrial plants from the infilled edges of the basin. Another variable factor will be the relative amount of basin-edge collapse or erosion of sediments resulting, for instance, from lowered water levels (chapter 6). The trophic state of the basin water, the relative amounts of compaction and sediment disturbance, and the relative amounts of chemical alteration, will all play additional roles in influencing the relationship between lithostratigraphic and biostratigraphic boundaries in peat deposits.

4. PROBLEMS OF RE-SEDIMENTATION OR OF NON-CONTINUOUS SEDIMENTATION

While serious stratigraphic disturbance (distortion and folding of sedimentary layers) is discounted (see Introduction), there is the possibility of the re-sedimentation of older deposits from the edges of basins resulting in the incorporation of younger material in the continuous sedimentation at the centres of the basins. Thus, though there is no sedimentary disturbance at the centre of a basin, there can be serious distortion of pollen spectra. Evidence that this has occurred in the basins studied in this thesis is provided by the analyses of deteriorated pollen grains (chapter 6) which suggest that redeposition of peat from the edge of the basins, either through active erosion or through the collapse of unconsolidated deposits as a result of lowered water-tables, has occurred. Unfortunately it is extremely difficult to identify non-contemporaneous redeposited pollen and so this factor, which has serious implications for the reconstruction of vegetation history and for radiocarbon dating, cannot be discerned from normal pollen diagrams. It is also difficult to determine whether or not this process has occurred from an inspection of lithological data alone. The possibility of redeposition is an important factor to be considered when correlating pollen assemblage zones from the individual pollen diagrams, and this is therefore further discussed in chapters 6 and 7.

Another serious stratigraphic problem that directly affects pollen zonation schemes is the possibility of a stratigraphic hiatus and, in terms of relative dating, the possibility of a delay between the formation or deglaciation of a basin and the commencement of sedimentation. On lithostratigraphic grounds there is no reason to suspect a major hiatus within the sediments described here, though often this is difficult to determine where there is a sharp boundary in peat stratigraphy or between minerogenic and organic deposits. The biostratigraphic data support this conclusion, except at two levels in two of the diagrams. Firstly, between 954 cm and 964 cm in the Amulree 2 diagram (Fig. 22) there is a transition from compact, sticky grey clay to a wetter and lighter grey clay. No pollen grains were found at this level, and there are some significant changes in the pollen spectra with a decline in Empetrum pollen, and increases in Pinus and Betula pollen and in Lycopodium and Selaginella spores. Secondly, in the Tynaspirit 1 pollen diagram (Fig. 16) between levels 460 cm and 480 cm there is a gap in the pollen record as sediment samples here were almost devoid of pollen grains. There are also marked vegetational changes at this level, and in fact the pollen zone boundary Tlg/Tlh occurs between 460 and 480 cm. There is, however, no break in lithology at this level.

A much more difficult problem relates to the possible delayed commencement of sedimentation within the basins under study. The earliest pollen records and radiocarbon dates give only the minimum age of formation or of deglaciation of a particular basin, and there is a possibility of a wide difference between actual deglaciation and the earliest sediment accumulation for a variety of reasons. One of the main reasons for a possible age difference of this kind is the likelihood of drainage through the underlying sediments before pore-filling by minerogenic and organic detritus permits the formation of a basin lake and hence the accumulation of basin sediments. It is therefore preferable to use sites whose bases are below local water-table. In the Teith Valley the bases of all of the sites are above the level of the River Teith. However, the full Lateglacial pollen records from Cambusbeg and Tynaspirit, the early Lateglacial radiocarbon date from Tynaspirit 2, and the pattern of an early immigration flora before the Juniperus peak in the basal sediments at Mollands all suggest that delay in sedimentation is not a severe problem at these sites. The base of the Amulree site is well below the level of the present course of the Girron Burn (Fig. 13). The possibility of a serious delay in sediment accumulation does exist at Glenturret (see Fig. 26).

The Glenturret basin is a completely enclosed hollow situated within hummocky moraine deposits (Fig. 7, and chapter 2). Because of its position it was assumed that early Flandrian deposits would have accumulated in this basin following the decay of the Loch Lomond Stadial ice. However, the Empetrum-Salix phase, the very characteristic Juniperus peak, and the dominant Betula phase that precedes the Betula-Corylus stage, which are all characteristic of early Flandrian deposits at the other sites, are not represented in the basal sediments at Glenturret. The bottom sediments at Glenturret record high percentages of Corylus in addition to Betula and thus show that the sediments at Glenturret began to accumulate after the Corylus rise, which has been dated to sometime after 9,260 B.P. in the Teith Valley and after 9,115 B.P. at Amulree (see chapter 4). This therefore indicates either extended free drainage at this site after the melting-out of Loch Lomond Stadial ice, or the accumulation of coarse minerogenic sediments during the early Flandrian (perhaps related to the collapse of unconsolidated deposits from the edges of the basin?), or the possibility of much delayed ice-melt at this site. Each of these three possibilities renders difficult the application of pollen studies to the dating of the Loch Lomond Stadial ice-limits. On the first possibility several areas of hummocky moraine are known in Scotland with completely underground streams (J.B. Sissons, personal communication). The possibility of sedimentation delay in a hollow formed in moraine has important implications for all sites that lie above local water-table, and may prove to be a recurrent problem for sites in hummocky moraine in Scotland. The possibility of delayed ice-melt is not improbable where there is the possibility that ice could have been buried in thick drift. Studies in North America have shown that ice can remain up to 1500-2000 years after the deglaciation of the surrounding area (Porter and Carson, 1971).

In addition it must be pointed out that Lateglacial and early Flandrian sediments are frequently absent from basins far beyond the limits of the Loch Lomond Stadial. A number of basins in south-eastern Scotland with gravel or sandy bases contain Flandrian deposits only, yet they are at relatively low altitudes and outside the Loch Lomond Stadial limits. The conditions controlling the beginning of deposition within basins are extremely difficult to determine. For example, Newey (1965, 1968) found that peat accumulation did not commence until the middle Boreal or Atlantic in some sites in south-east Scotland. As with such lowland sites in sand and gravel deposits, waterlogging in an upland basin, such as Glenturret, may be dependent upon the formation of a perched water-table. Thus, initially, water may have been able to percolate down through the generally coarse deposits, eventually draining towards the valley bottom. Percolating water may have carried down fine particles of clay and silt which, over a period of time, may then have accumulated at depth within the coarse deposits to form a layer of compacted silt and clay. This would result in the production of an impervious layer, allowing the build-up of water within the Glenturret basin and thus the accumulation of organogenic sediments. On a local scale perched water-tables can also arise as a result of pedogenesis, with the formation of an iron pan within the solum (Cruikshank, 1972).

It is therefore considered that the first of the three possibilities listed above seems the most likely, that there was extended free drainage at Glenturret until the formation of an impervious layer within the surrounding deposits. Thus the formation of an enclosed hollow within glacial melt-out deposits is not of itself sufficient to result in immediate waterlogging within the depression, for factors such as local water-table and the material of which the deposits are composed are important. If it is assumed that the Glenturret depression was vacated by ice at the close of the Loch Lomond Stadial, then it took well in excess of 1,000 years for an impervious layer to develop at Glenturret to create a local perched water-table (see chapter 12).

5. VARIATION IN GRAIN-SIZE AND COLOUR OF MINEROGENIC SEDIMENTS

Laminated sediments, or rhythmites, were found at two sites, Amulree and Mollands. At Mollands the lamination is produced through a variation in grain-size only in the minerogenic sediments, but at Amulree both grain-size and colour variations occur in the clay deposits. A detailed account of the lithological records from both of these sites is given in chapter 2.

At Mollands sand and gravel gives way to alternate layers of fine sand and clay. These in turn are superseded by alternate layers of clay and gyttja before a final alternation of thin bands of gyttja and peat gives way to Flandrian peat. Three features are considered to be of importance in the basal sediments at Mollands; the very characteristic green colour of the gyttja, the periodicity of the rhythmites, and the change to organic deposition.

The greenish colour of gyttja is a common characteristic in some continental basin sediments. Faegri and Iversen (1964) reported that:

> "Pure gyttja consists of microscopic and submicroscopic remains of the flora and fauna of the basin. As this flora and fauna vary, the gyttjas vary, but they have in common that they are insoluble in KOH and that the extract is never dark brown, but yellowish, greenish, or almost colourless. Unchanged plant pigments, especially carotenes, are frequently found in gyttjas, and so are also some green pigments, which are most probably chlorophyll derivatives ..." (page 43).

Samples from the thin bands of gyttja and thin bands of peat were examined before and after laboratory preparations. The pale green colour of the gyttja samples appeared to be much paler than had been remembered from field examination. Some samples were left exposed to the air and after a few days were found to turn much paler in colour, with white or grey particles becoming apparent, and the green colour tending towards a yellowish-brown. However, the greenish component was found to affect only a very small proportion of the samples studied. After laboratory preparation, clay was recovered from the washing treatment of the green gyttja samples but rarely, and only in very small amounts, from the adjacent peat bands. Treatment with hydrofluoric acid was never required for the gyttja samples as they were extremely rich in microfossils. No difference in pollen spectra was detected between adjacent gyttja and peat samples.

The green colour may indirectly relate to the clay component of gyttja. If the colour originates from accumulated chlorophylls and carotenes it may be that this can only occur under specific conditions. It is suggested here that the clay relates to rapid snow or ice-melt which resulted in the periodic accumulation of clays in the Mollands lake. This may have resulted in rapid changes in the flora and fauna of the lake, or, more likely, in the degree of reduction within the lake waters. The colour change of samples in the laboratory as a result of aeration suggests the green colour to be a result of extreme lack of oxygenation, possibly as a result of the clay sediment load in suspension, but more probably as a result of rapid sedimentation of minerogenic and fine organic particles. Gyttjas are characteristic of eutrophic lake waters (Faegri and Iversen, 1964) and thus the rapid accumulation of both minerogenic and organic particles might account for the preservation of the pigment colouration. There is the possibility that the alternating laminations of green gyttja and brown peat represent spring melt of snows or ice resulting in the gyttja-clay material, and the summer accumulation of organic detritus (brown peat). In any case the green gyttjas and lower clay laminations probably indicate the close proximity of ice, or heavy snow-melt.

The alternating laminations of minerogenic sediments and the alternating minerogenic and organic laminations indicate some periodicity in the deposition rate of the sediments within the Mollands lake. That this periodicity may have been annual in character, implying that the rhythmites are varves, is an obvious hypothesis, but may be too simple a suggestion. The coarse layers towards the base are extremely thick and non-continuous in some instances. Thus the gravel layer recorded in cores 8 and 9 (Fig. 12) is seen to 'wedge-out' into a sand horizon. However, the thin clay and sand layers recorded in cores 7, 8, 9 and 10 were extremely regular in appearance, and were not contorted. It is difficult to determine the exact number that occur between 716 cm in core 7 and 766 cm in core 10 since the exact sequence could not be followed between adjacent cores. Counting was nevertheless attempted and suggested between about 45-60 rhythmite pairs of sand and clay laminations. A further 20 clay and gyttja rhythmite pairs were recorded, and 12 paired laminations of gyttja and peat. Some of the gyttja layers were extremely faint, being about or less than 0.5 mm thick. One of the peat layers in the latter group was almost 1.5 cm thick, which seems too thick a layer to have accumulated in only one season. At such a rate the Mollands basin would have been completely infilled in just 550 years. Between the coarsest basal sediments at Mollands and the Flandrian peat there is a sequence of between 75 and 90 rhythmite pairs.

The third important feature of the basal sediments at Mollands is the gradual change from purely minerogenic to purely organic deposition throughout the Loch Lomond Stadial-Flandrian transition. This contrasts markedly with all of the other sites. The transition between Loch Lomond Stadial clays and Flandrian organic deposits is a sharp boundary at Cambusbeg 1, Tynaspirit 1, Tynaspirit 2, and Amulree. At sites that did not receive Loch Lomond Stadial ice meltwaters the production of Loch Lomond Stadial clays was a result of soil disturbance on local slopes. The end of the Loch Lomond Stadial period is thus marked by the termination of soil disturbance and the development of a closed vegetation cover, which are interdependent factors. A slow accumulation of Loch Lomond Stadial clays and rapid development of vegetation would thus result in a sharp change from clay to organic deposition, which occurred in most Scottish Lateglacial pollen sites.

At Mollands the production of clay deposits appears to be an independent factor. Clay is recorded within the gyttja deposits up to about 705 cm in core 7 (Fig. 25). The pure clay layers are devoid of pollen, but the extremely thin gyttja bands (less than 0.5 mm) down to a level of 725 cm record abundant pollen content throughout, and the establishment of a local stable vegetation at 716 cm is reflected in the percentages of Salix, Empetrum, Rumex and Betula. A small clay content is also recorded in lithostratigraphic unit 6 where the Juniperus percentages (pollen sub-zone Mob II) must indicate a stable soil locally. Thus the clay recorded at least between levels 725 cm and 705 cm probably relates to minerogenic material brought into the basin by streams emanating from melting snow or ice rather than from locally disturbed soils.

Laminated clays have also been recorded from the basal deposits at Amulree (see chapter 2), but at this site this involves variation in colour and little perceptible change in grain-size. Between 1044 cm and 1072 cm in core 25 (Amulree 2, Fig. 22) distinct but thin laminations of pink and grey clay were recorded. One pink band and adjacent grey band may together measure as little as 1.0 mm, but on average measured about 2.0 - 3.0 mm in thickness. Pollen was extremely thin in both the pink and the grey clay layers, and pink samples were usually devoid of pollen.

Between 1030 and 1044 cm (core 25) what at first appeared to be a constantly faint pink clay was later found to give indications of banding after cutting and drying in the laboratory. Similarly, the lower 15 cm of the compact grey clay (lithostratigraphic unit 3, Fig. 22) also showed very faint indications of banded clays after drying.

The total number of pairs of laminations between 1015 and 1072 cm was extremely difficult to determine. Often the definition of suites of bands, especially between 1015 and 1044 cm, was obscure, and at some levels there appeared to be three different layers, a dark grey layer, a pale grey layer, and a pink layer. The clearest layers were those in lithostratigraphic unit 1, and these layers often split after drying. The split was always between the lower boundary of the pink clay and the upper horizon of the grey clay, and was sometimes marked towards the base of the sediments by a very thin layer of fine sand or silt. An estimate of the total number of pairs of clay laminations between 1015 and 1072 cm is ca. 250. If one considers that at Amulree 1 pink clays were recorded between 1010 cm and base (1200 cm), and if it is postulated that pairs of pink and grey clay laminations are annual rhythmites, then this would imply a very long period of clay accumulation in the Amulree basin.

Laminated pink clays have previously been reported by Pennington (1964) and Newey (1970), and laminated grey Lateglacial clays by Seddon (1962), Crabtree (1972), and Birks (1973). No detailed explanations of the pink colouration have yet been published. Birks (1973) noted that some grey clays tended to have a red iron staining on drying or exposure to air. In the samples from Amulree the red clays tended to change their colour, the pink colour becoming fainter and eventually changing to a pinky-grey colour on exposure to air. In a study of pink clays in Somero, Finland, Donner and Gardemeister (1971) found that the pink colour was associated with the coarser summer layers of varves. The source of the pink clay at Somero was the redeposition of Eemian clays, and it was found that the pink colour was caused by ferrous oxide (Fe_2O_3) which turned grey when reduced by hydrochloric acid (HCl). The grey clay layers at Somero were the winter layers of the varves and were found to be much richer in microfossils than the pink clays, which contributed towards the colour change. The cause of the pink colour at Amulree is unknown, but the change from pink to grey colour under oxidising conditions (aeration) differs from that reported by Donner and Gardemeister. However, the association of fine silt layers at the base of some pink clay layers at Amulree suggests comparison with the "summer layers" at Somero. A detailed chemical analysis of the Amulree clays is required before the implications of the alternating colour changes can be expanded.

There are two marked contrasts between the Amulree basal sediments and those at Mollands that suggest very different environmental records in these two sites. The first is in the laminated pink and grey clays at Amulree, which is not repeated at any of the other sites, and suggests production of the pink clays under special chemical conditions, or alternatively the supply of fresh pink minerogenic deposits. If it is suggested that the laminated clays are rhythmites produced by variations in snow or ice-melt during the Loch Lomond Stadial period, then either this site records a detailed Loch Lomond Stadial/Flandrian transition, or it records a long period of ice-free but fluctuating conditions. If a detailed Loch Lomond Stadial/Flandrian transition interpretation is proposed, then it would be difficult to account for the absence of the gradual minerogenic-organic transition that is recorded at Mollands. The pollen records at both these sites are also very different (chapter 4). The Flandrian vegetational history suggests that Amulree, like Mollands, is a relatively eutrophic site, and the development of a transitional gyttja deposit might have been expected.

In continuing this argument the second contrast between Amulree and Mollands is important. The transition from minerogenic to organic deposition at Amulree at the Loch Lomond Stadial/Flandrian boundary is abrupt, as it is in the Lateglacial sites Cambusbeg and Tynaspirit. This suggests that the supply of clay at this time was from the soils from the local slopes and not from local ice meltwaters (see above). It therefore seems that the Amulree sediments record a much different environmental episode to that recorded at Mollands, and the deep layer of fine clay deposits at Amulree (nearly 4.0 m) is attributed to an extremely long period of accumulation.

6. BIOSTRATIGRAPHICAL DISTORTION CAUSED BY CONTAMINATION

Contamination of older deposits by younger micro- and macrofossils is a rare problem when sampling is based on a stratigraphic section, unless percolation by ground-water or severe disturbance by plant or animal acitivity has occurred. Normally such sections would be abandoned. However, when a study is dependent on sub-surface basin deposits then a degree of contamination is often unavoidable. The diagrams presented in this thesis show that contamination is caused by the use of an auger boring mechanism, such as the Hiller sampler, and that this is particularly severe when sampling Lateglacial minerogenic deposits.

The tendency for the Hiller auger to distort sediments during sampling is clearly demonstrated at three of the sites. Initial sampling by large Hiller at Amulree revealed pink coloured clays at depth (Fig.20) but no laminations could be discerned. Later sampling at Amulree by piston corer revealed numerous clear laminations of pink and grey clay (section 5 above). The Hiller had distorted the sediments in such a way that the laminations were completely obscured, and the pink clays often appeared as mottles within dominantly grey clay, which was extremely difficult to interpret. Similarly, re-investigations at Mollands using a piston corer discovered grey laminated clays (Fig. 25) that had not been recorded after using the Hiller sampler. At Cambusbeg basal grey clay samples were found to be contaminated by a film of brown organic mud only after close inspection in the laboratory. The Hiller appears to have carried down organic mud, probably coated on the outside of the chamber, and then this was incorporated into the clay samples during the operation (opening and closing) of the chamber.

There is no clear evidence for distortion of peat stratigraphy, or other organic deposits, but this would in any case be difficult to recognise. The horizons within the peat stratigraphies recorded at each site are usually sharp. This may partly be explained by the fact that sampling in peat was usually very easy, where downward penetration of the sampler was usually rapid. In the basal minerogenic deposits of Amulree and Mollands progress was very slow, the deposits at both sites being very compact, requiring much turning of the Hiller auger for a relatively small amount of penetration.

The Hiller therefore affects sediments in two ways: firstly, by distorting the sediments (and thus pollen assemblages) through the action of the auger, and secondly by the incorporation of younger material that has adhered to the chamber into older deposits as a result of the passage of the borer through younger deposits. This latter occurrence is a severe source of error (Jowsey, 1966), and has resulted in unmistakable contamination, particularly in Lateglacial minerogenic sediments (chapter 4). Where the Hiller has passed through organic deposits to sample lower organic deposits contamination is not obvious. This is because the amount of microfossil contamination may be extremely small in comparison to the total microfossil content of the sampled sediments. However, where the sampler has passed through organic deposits rich in microfossil content into deposits, such as Lateglacial clays, that are extremely poor in microfossil content, then a minimal amount of contamination can seriously distort the pollen spectra. For instance, if it can be assumed that the basal minerogenic sediments in a Lateglacial site were deposited at a time when plant immigration following deglaciation of the surrounding landscape was of a true pioneer nature, such as mosses, ferns and herbaceous colonisers of bare minerogenic soils, then the total absolute pollen and spore influx into the basin would be exceedingly low in comparison to that received at upper levels. Any contaminants carried down by the sampling equipment, though possibly small in volume, or in number in absolute terms, can assume significant proportions in a relative frequency diagram. If the probability of rapid minerogenic sedimentation is also considered, which would result in low pollen concentrations, then it becomes apparent why only a minimal amount of contamination by modern pollen can have serious effects on the resultant diagram (see Appendix 2).

There is evidence for microfossil contamination in basal minerogenic deposits at Tynaspirit 1, Cambusbeg, Amulree 1 and Mollands (chapter 4). This is most readily revealed by the presence of Corylus pollen in pre-Flandrian sediments. Contamination of Lateglacial sediments by the incorporation of younger material has previously been suggested as the explanation of records of Corylus in Lateglacial sediments by Oldfield (1960), Bartley (1962, 1966), and Pennington (1970).

The total amount of contamination that has affected those Lateglacial diagrams based on samples obtained by Hiller may seriously distort both the composition of individual pollen spectra and the trends in pollen curves in the Lateglacial zones. This must be particularly serious in the Loch Lomond Stadial clays. The herbaceous pollen totals of the Stadial pollen zone (T2d) of Tynaspirit 2 (Fig. 17) achieve much higher totals than those of the Stadial zone (T1d) of Tynaspirit 1 (Fig. 15). While this may be the result of statistical variations between the sites, or of the closer sampling interval at Tynaspirit 2, there is the possibility that this reflects the depression of the herbaceous pollen totals in T1d as a result of contamination by other taxa. This may also account for the poor definition of the Loch Lomond Stadial pollen assemblage zone in Cambusbeg 1 (Fig. 18). At this site percentages of Corylus as high as 11% are recorded in the basal minerogenic deposits, and the Juniperus curve is very complex and difficult to interpret. Another diagram seriously affected by contamination is that of Mollands, Fig. 23, based on samples obtained by small Hiller. Here Corylus percentages are as high as 13% in sediments laid down earlier than the early Flandrian Juniperus peak.

In the Amulree 1 diagram (Fig. 20) there is a pattern that, to a variable degree, may be repeated in all of the diagrams based on samples obtained by Hiller. In zone Am1f percentages of Betula and Juniperus are high, and decline markedly downwards in the diagram into zone Am1e. Betula and Juniperus increase quite markedly again at the top of zone

Am1d, the Loch Lomond Stadial zone. This might be interpreted as a slight climatic oscillation, or variation in the rate of pollen influx of different taxa. However, on the evidence presented above, it is probably related to contamination. If deposits from zone Am1f are carried down into contact with deposits of zones Am1e and Am1d then this may not seriously affect the pollen spectra of zone Am1e, where the pollen content is high, but would seriously affect the pollen spectra from the minerogenic deposits of zone Am1d, where the pollen content is extremely low. This would most affect the upper sediments of zone Am1d. It is concluded, therefore, that the increase in percentage of <u>Betula</u> and <u>Juniperus</u> pollen in upper zone Am1d is artificial and does not relate to actual vegetational changes. The Amulree 2 pollen diagram (Fig. 22) supports this conclusion in that increased <u>Betula</u> and <u>Juniperus</u> pollen totals are not repeated in the upper Stadial clays (zone Am2e) at this site where sampling was by piston corer.

Despite care in operation of the sampler in the field, handling of the samples in the field, and inspection of the samples prior to laboratory preparations, contamination still affected those minerogenic sediments obtained by Hiller sampler. The amount of contaminant material, in volumetric terms, must have been exceedingly small as it was undetected by eye in the samples analysed in the laboratory. Such significant contamination in terms of the resultant pollen spectra reflects the exceedingly low influx of pollen in Lateglacial clays. Such a serious error must indicate the questionable results of pollen diagrams based on Lateglacial minerogenic sediments that have been obtained by Hiller sampler. It is therefore imperative to recognise this factor when comparing Lateglacial pollen diagrams as indicators of vegetational development (chapter 8). In correlating the local pollen assemblage zones for the Lateglacial period in southern Perthshire emphasis will be on those diagrams based on samples obtained by piston corers, <u>viz</u>. Tynaspirit 2 and Amulree 2 (chapter 7).

7. THE PROBLEM OF LONG-DISTANCE TRANSFER OF POLLEN GRAINS

This factor, the second of Faegri and Iversen's (1964) "classical sources of error", has been discussed in general terms in chapter 1. Though Faegri and Iversen claimed that "... the quantity of pollen produced by local vegetation is generally so immense that the quantities deriving from long-distance transport are relatively insignificant despite their absolute magnitude" (p.117), it is generally considered that too little is known about the effect of wind-transported pollen, particularly in Lateglacial pollen diagrams. A growing number of publications have recently demonstrated the effect of wind-transported tree pollen in diagrams from present-day tree-less areas (Aario, 1940; Bartley, 1967; Lichti-Federovich and Ritchie, 1968; Birks, 1973; Tyldesley 1973a, b, and c), and Nichols (1970) has shown this to be an important source of error in Lateglacial palynological data.

It is important to decide whether a significant increase in the percentage of a wind-transported pollen type actually reflects immigration of that particular taxon into the local area around the basin under study, or whether it reflects an increase in the relative amount of long-distance wind-transported pollen, either because of an increase in dispersal at the source, or because of some change in atmospheric conditions. Where the local rate of pollen influx is high, any pollen grains deriving from long-distance transport will play an insignificant role in the pollen spectra, but where the influx is low, pollen derived by long-distance transfer will be emphasised in the pollen diagram.

A number of grasses and sedges that commonly dominate the flowering plant component of arctic vegetation are anemophilous and liberate abundant wind-borne pollen grains. A number of moss species (e.g. species of Lycopodium) also release abundant spores, and certain dicotyledon herbs (e.g. Rumex acetosa) are noted for producing enormous quantities of pollen (Faegri and Iversen, 1964). However, the majority of plants in arctic and alpine environments are insect-pollinated, though wind pollination is more common in arctic than in alpine areas, and becomes increasingly more important with increasing latitude (Billings, 1974). Information is now available for characteristic absolute pollen deposition in lakes in arctic and alpine environments (Ritchie and Lichti-Federovich, 1967; Fredskild, 1973), and comparisons between these published data and absolute pollen counts from Lateglacial spectra from Scotland and the Lake District has enabled Pennington (1977) to recognise "pollen-poor" and "pollen-rich" Lateglacial sediments. During the Loch Lomond Stadial and the early pioneer phases of the Lateglacial Interstadial, variation in the degree of vegetation cover and in the importance of anemophilous plants in the local flora would have resulted in a wide variation in total pollen influx between different sites. Where the total influx of pollen grains from the local terrestrial vegetation was low this may have resulted in the over-representation of pollen grains of anemophilous trees and shrubs transported over long distances

It is commonly accepted that percentages for Pinus pollen that are generally below 10% in a pollen diagram do not indicate the presence of Pinus in the immediate vicinity of the corresponding site (Faegri and Iversen, 1964; Vasari and Vasari, 1968). On that criterion Pinus was only established close to the basins studied in this thesis as follows:-

(a) MOLLANDS (Fig. 24): Pinus percentages generally increase to over 10% in zone Moe; percentages generally in excess of 30% indicate the presence of Pinus in zone Mof; Pinus percentages decline throughout zone Mog to become insignificant in zone Moh.

(b) TYNASPIRIT 1 (Fig. 16): Pinus percentages increase to over 10% only in the upper part of zone Tlh; this may equate with zone Moe as an indication of the establishment of Pinus within the Teith Valley.

(c) AMULREE 1 (Fig. 21): Pinus percentages increase in the upper zones of this site but in only one spectrum is there a Pinus percentage of greater than 12% of total arboreal pollen; the percentages fluctuate throughout and this may indicate pollen derived by air transport from a nearby source rather than the presence of Pinus in the local area.

(d) GLENTURRET (Fig. 26): Pinus percentages attain a constant 10% or over in the upper part of zone Glb, and the high percentages in zones Glc and Gld indicate a local source that disappears in zone Gle.

With the exception of these zones Pinus, though an almost constant constituent of the pollen spectra in each diagram, is not regarded as having had a local source in southern Perthshire, and seems to have always been restricted in ground cover. However, it is not known how critical the value of 10% is in reality when applied especially to percentages of Pinus pollen in the context of the Scottish Highlands.

Pinus forest was never established in the Lateglacial vegetation at least in northern England and Scotland (see chapter 1). The records of Pinus in Lateglacial deposits therefore give some indication of the extent of long-distance transport and the relative rates of pollen influx throughout the Lateglacial sediments. Pinus pollen is recorded throughout the Lateglacial sediments in Cambusbeg, Tynaspirit and Amulree, and in the Loch Lomond Stadial/Flandrian transition deposits at Mollands. It is doubtful that this relates to sampling contamination since sediments sampled by enlarged piston corer (Amulree 2, Fig. 22; Mollands, Fig. 25) also exhibit significant percentages of Pinus pollen in basal minerogenic deposits.

The percentages of Pinus pollen within the Lateglacial zones are usually higher in the early Interstadial and Loch Lomond Stadial sediments. This is particularly noticeable in the Amulree 2 pollen diagram (Fig. 22), where Pinus percentages increase in zones Am2a, the lower part of Am2b, and in zone Am2e. In general, sharp consistent increases in the percentage of pollen of a particular taxon can either be explained by an increase in dispersal of pollen of that taxon at the source (increasing crown or ground cover), or, in the case of diagrams based on relative frequencies, by a reduction in the rate of pollen influx of other taxa. The first explanation is thought to be unlikely since during the Loch Lomond Stadial, for instance, the Pinus forests would have been much reduced during the increasingly harsh environment over most of north-west Europe. Percentages of Pinus pollen of up to 16% in zone Am2a probably reflect the influence of a very low rate of influx of pollen of local taxa.

An important sedimentation phase is indicated in sub-zone MoaI of Fig. 25b. In this zone Pinus percentages are as high as 26%, an exceedingly high value for a period when there could have been no pine forest in this region. This must indicate the extremely poor pollen influx into this basin at this time. The sedimentation rate appears to have been high (see above), much higher than the minerogenic accumulation rates at Amulree, Cambusbeg, and Tynaspirit. Yet the highest percentages of Pinus pollen derived from long-distance transfer are recorded at Mollands. The extremely low rate of influx of pollen from local taxa has resulted in much inflated values for pine pollen. The local slopes around the basin must have had a poor vegetation cover at that time, with possibly a lichen and moss heath developing immediately following deglaciation of the basin.

The Amulree 2 pollen diagram (Fig. 22) is also important in pointing to the possibility that some of the Betula pollen grains recorded in the Lateglacial sediments may in fact be derived from long-distance transfer. Betula pollen totals also increase markedly in zones Am2a, Am2b and Am2e, which is not consistent with the general interpretation of the diagram (see chapter 4). This indicates the possibility that some of the birch pollen recorded in Lateglacial and early Flandrian sediments from other pollen sites may in fact derive from long-distance transfer of arboreal birch pollen. A major difficulty, however, is that no attempt has been made to separate Betula nana and arboreal Betula pollen grains in any of the diagrams with the exception of Mollands (Fig. 25). From Fig. 25 it can be seen that a Betula nana phase occurs in sub-zones MobI and MobII. The total Betula pollen curve records much higher percentages and it may be that much of this is arboreal pollen derived from a regional or extra-regional source, before the local immigration of tree birch. This may especially apply to zone Moa.

There is little known about the effects of long-distance transfer of arboreal pollen of Betula and of other taxa in British Lateglacial pollen diagrams. For instance, there are the curious records of Quercus and Alnus from Lateglacial deposits and from Loch Lomond Stadial/ Flandrian deposits (zone Am2e, Fig. 22; sub-zone MobIII, Fig. 25). The most valuable indicator of this source of error is the Pinus pollen curve. It indicates the greatest distances that wind-transported pollen can travel, especially since it is believed that Pinus was a minor floral component even in southern England in Lateglacial Interstadial times (see chapter 1). It also indicates horizons where a low rate of pollen influx is an important characteristic of sedimentation.

8. THE PROBLEM OF LOCAL OVER-REPRESENTATION OF TAXA

The value of pollen diagrams as records of regional vegetational history is much reduced where the pollen influx exaggerates the representation of particular taxa. This can result from the presence of a heavy pollen producer, such as Pinus, Alnus, or Betula, in the immediate vicinity of the basin sediments on which the pollen diagrams are based. Some correction factors for certain arboreal genera that are recognised as heavy pollen producers have recently been suggested (Andersen, 1967, 1970, 1973). However, this field of investigation is very complicated and has not yet been studied in detail, particularly with regard to the application of such factors to pollen diagrams in Britain. Further, many entomophilous taxa that are common in tundra areas (e.g. species of Compositae and Caryophyllaceae) are under-represented in pollen diagrams.

Another way in which regional vegetational components in general can be undervalued in pollen diagrams is by the local over-representation of pollen of taxa contributing to the local hydrosere developments. Local site factors, especially the depths of the basins and the trophic status of the lake waters, are extremely variable and result in major differences in the local abundance of particular taxa in the various successional stages, and in the length of time required for the development of suitable conditions for the final stage, the invasion of the climax community. The pollen diagrams in this thesis differ widely in the representation of the natural hydrosere succession. In some the stage of free-floating plants, the reed-swamp stage, the sedge-fen communities, Sphagnum moss accumulation, and a phase of shrub and tree invasion of a dried bog surface are well represented in the pollen spectra.

Figure 24 indicates clearly a full hydroseral sequence at Mollands. A rich aquatic flora became established during pollen zone Mod, with Potamogeton by far the most dominant aquatic pollen type. However, primary mire development must have occurred quite rapidly during zone Mod, for Equisetum spores and pollen of Gramineae, Cyperaceae, and other herbaceous families all expand quite markedly in this zone. The marked rise of Equisetum, probably indicating mostly the species Equisetum fluviatile (Vasari and Vasari, 1968), and the virtual disappearance of aquatic pollen by the close of zone Mod, indicate predominantly shallow water conditions in the basin and the expansion of marsh vegetation at this time. During zones Moe and Mof the basin must have been subsequently almost infilled with peat, for Salix shrubs and trees were able to expand over the peat deposits and mire surface that had developed from the edge of the basin.

The hydroseral sequence and its relationship to other vegetational developments at Mollands, as indicated by the pollen assemblages, are discussed more fully in chapter 11. It is important here, however, to note that the development of a thick shrub and tree cover on the bog surface at Mollands, dominated by Salix spp. but also possibly including Alnus and Betula spp., would have seriously affected the pollen rain and pollen filtration (Tauber, 1965, 1967) incorporated into the sediments that were still accumulating at the centre of the basin. Thus the local over-representation of certain tree and shrub genera may possibly mask the representation of taxa that are important in the regional vegetation cover.

At Glenturret (Fig. 26) an equally well-marked hydroseral sequence is recorded. Aquatic pollen grains are recorded throughout the analysed sediments, but at the Glb/Glc pollen zone boundary they almost disappear from the pollen assemblages. As with the Mollands diagram, the very high percentages of Gramineae, Cyperaceae, and other herbaceous genera probably reflect the expansion of the marginal reed and sedge communities within the basin, and the excessively high percentages of these taxa must be taken into account when interpreting the generalised pollen diagrams (given in each diagram following the arboreal pollen sums). Salix is recorded in significant percentages throughout the Glenturret pollen diagram, probably reflecting the growth of shrubs and trees of Salix over the infilled parts of the basin. This is particularly well-marked in zone Gld, when the basin may have been almost completely filled in.

At Amulree (Fig. 21) the hydrosere sequence is again fully represented, but Salix does not dominate the late hydroseral stages as at Mollands and Glenturret. Instead, Ericaceae and Empetrum are locally dominant, and a much wetter, looser Sphagnum peat had accumulated at this site. At Tynaspirit (Fig. 16) and Cambusbeg (Fig. 19) the aquatic pollen content of the pollen assemblages from the sampled sediments indicates that lake waters were present throughout, and an expanding primary mire is not indicated in the pollen records from these two sites.

Thus, between the five sites there is variation in the extent to which the basins have been infilled by the production of autocthonous and allocthonous organic detritus, especially of that resulting from local primary mire development. Conditions were especially suitable at two of the sites (only a partial pollen diagram is available from Tynaspirit: it is probable that the upper sediments at this site also record a dominant Salix phase) for the expansion of Salix shrubs and trees onto the surface of the expanding and drying mire, and this will probably have affected the composition of the arboreal pollen influx. Thus in comparing the forest histories recorded at the five sites (chapter 11) possible local distortions of the pollen spectra as a result of local over-representation of taxa must be taken into account.

9. CONCLUSIONS

Not all of the problems encountered in palynological interpretations have been covered in this chapter. For instance, the problems of variation in pollen production between various taxa, and the problems of statistical representation in general, have been omitted. Those problems that have been discussed are regarded as being the most serious sources of error, especially in Lateglacial and early Flandrian spectra. In addition there is specific evidence from the relative frequency pollen diagrams and the stratigraphic records of each of the five sites for the relative amount of distortion resulting from each source of error.

As a result of the discussions in this chapter it is possible to rank the sites in terms of the suspected overall distortion of the regional and local pollen assemblages. In this respect Tynaspirit 2 (Fig. 17) is designated the type-site for the Lateglacial vegetational developments, since the lithological and biostratigraphical criteria are clear, and the effects of distortion as a result of any of the sources discussed in this chapter appear to be at a minimum. For similar reasons Mollands (Fig. 25) is the type-diagram for the Loch Lomond Stadial/Flandrian transition period, though some care is required for interpretations within zones Moa and Mob. No one particular site is regarded as a type-site for later Flandrian developments.

One serious possible source of error has not yet been discussed, however, and that is the problem of deterioration of pollen and the effect of this on the pollen spectra. This is discussed in the following chapter, and all the possible sources of error are taken into account in the correlation of the local pollen assemblage zones for the various sites (chapter 7, tables 4 and 5).

CHAPTER 6

The Analysis of Deteriorated Pollen Grains

1. INTRODUCTION

Two major problems encountered from the outset in attempting to record and analyse the deteriorated pollen content of pollen spectra have been those of classification and subjectivity. It is difficult to classify the condition of pollen exines because of the great range of deterioration intensity, variation in type of deterioration, different theories as to the causes of deterioration, and because very little work has been done in this field of enquiry. Published work so far has concentrated on the identification of secondary pollen deposition or derived non-contemporaneous pollen, and the elimination of these from the pollen spectra. Not all deteriorated pollen grains originate in these ways, and much difficulty exists in deciding to what extent deteriorated grains consist of penecontemporaneous inwashed pollen (see chapter 3), and to what extent the deterioration is due to post-depositional processes.

The classification that has been applied in this thesis follows Birks' modification (1970) of the original classification proposed by Cushing (1964). The recognition of the attributes of the different classes - corroded, amorphous, broken, and crumpled (defined in chapter 3) - is quite straightforward, though difficulties arise where very slight modification of a pollen exine requires the very subjective assessment as to whether the grain should be classed as deteriorated or not. By far the greatest problem in classification concerns those grains that display more than one type of deterioration of the exine. Cushing (1967) suggested a hierarchy of deterioration classes comprising, in order, corroded, amorphous, broken, and crumpled grains. In his scheme a grain that displayed signs of corrosion and crumpling would simply be classed as corroded, a grain that was both amorphous and broken would be classed as amorphous only, and so on.

As the author had no previous experience in the analysis of deteriorated grains, Cushing's scheme was accepted. However, this scheme has the important implication that the types of deterioration highest in the classification are the most important. If a variety of causes of deterioration can be demonstrated, or proposed on theoretical grounds, then such a scheme only remains acceptable when one is concerned with a particular process. For instance, it might reasonably be suggested that corrosion indicates chemical alteration of the pollen exine, whereas breakage of grains, and possibly crumpling, indicate the physical processes of corrasion or of compaction. A pollen grain that is both corroded and broken may thus have been affected by two very different processes, and these processes need not have been active contemporaneously. This would therefore have important implications in any detailed analysis. The assignment of pollen grains to only one class of deterioration when evidence of more than one class is present is therefore an over-simplification, and this is pointed out here as a serious weakness in the deteriorated pollen diagrams presented in this chapter. No records were taken of the percentage of pollen affected by more than one type of deterioration. It is probably quite substantial, though certainly not as high as 50%. The author intends to develop a more detailed and more flexible classification system for future work on deteriorated pollen.

The second major difficulty in analysis, that of subjectivity, is met in three main ways:

(a) There is a problem with the degree of deterioration where very slight or faint evidence of deterioration results in difficult decisions as to the inclusion of certain grains within the deteriorated category. This is particularly difficult with partially obscured grains when using a solidifying medium.

(b) A second difficulty concerns those grains with exines that are easily modified and are commonly deteriorated in some way, even on type-slides prepared with fresh material. Juniperus and Cyperaceae grains come into this category (see chapter 3).

(c) There is a specific difficulty with the amorphous class where there is a range in the degree of this type of alteration, from those grains that are obviously modified to being opaque in appearance rather than transluscent, and where exine processes have lost much of their definition, to those grains that are only changed slightly from the normal appearance of the grains in a particular sample. Thus some grains appear only a little darker and slightly more opaque than normal, but not so significantly modified as others. Whether this is due to variation in the degree of amorphism, to variation in the uptake of the staining medium, or to variation in pollen chemistry, remains problematic.

Added to these difficulties are the factors of chemical preparation procedures and the direct effects of the mounting medium. Different chemical preparations have different effects on the pollen exine (Faegri and Iversen, 1964), and there is evidence for distortion and crumpling of grains as a result of using certain mounting media (Praglowski, 1970). Little is known about these factors. However, two arguments are advanced to suggest that the deteriorated pollen curves in this thesis represent real changes within the sediments, and that the results of post-sampling treatment or exposure are insignificant causes in the total number of deteriorated grains.

Firstly, samples from horizons 490 cm and 440 cm at Tynaspirit 1 (Fig. 16) were studied after using glacial acetic acid acetolysis and after acetic anhydride acetolysis (Erdtman's method). The proportions in number and type of deteriorated grains were found to be similar. An attempt to study sediment samples mounted in water with no chemical pre-treatment failed as pollen grains as a result were rare, difficult to see, and difficult to recognise because of a lack of definition of exine structure. Slides for the type-slide collection were prepared using glacial acetic acid acetolysis and were mounted in glycerine jelly. In addition some types had also been prepared by Erdtman's acetolysis and mounted in glycerine jelly. In none of the type-slides were there signs of the amount and character of deterioration recorded in the fossil spectra. Clay samples were particularly difficult to test, since without the use of hydrofluoric acid pollen grains were extremely scarce on resultant slides. An hydrofluoric acid preparation of fresh Betula pubescens grains produced shrinkage of an estimated 10-15%, without distortion or deterioration. A preparation of hydrofluoric acid followed by Erdtman's acetolysis resulted in slightly enlarged grains, again without distortion or deterioration. Though time did not permit an exhaustive study of the effects of laboratory treatment, there is nevertheless nothing to suggest that laboratory preparations in any way significantly affected the proportions of deteriorated to non-deteriorated pollen in the fossil samples.

Secondly, various deteriorated pollen curves revealed in the five frequency diagrams for deteriorated pollen (section 4) indicate seemingly logical trends and, more important, reveal similarities in trends between the various diagrams. Marked changes in certain curves of deteriorated pollen occur in one or more of the diagrams where the laboratory treatment has remained constant. For instance, the marked increase in deteriorated pollen in zones T1g and T1h at Tynaspirit 1 (Fig. 16) occurs where there is no change in lithology and where laboratory procedures remained constant throughout. It thus seems that the explanation of variation in deterioration of pollen within the various sediments, though by no means a simple task, need only consider problems of the depositional history of the sediments and their biogenic content, as well as post-depositional but in situ processes. Laboratory treatment and exposure of pollen are recognised as being possible contributing factors to deterioration of pollen in general, but they are not thought to play a major role in the diagrams presented here.

The deteriorated pollen content of the pollen spectra is analysed in two ways. Firstly, an analysis of the overall total amount of deteriorated pollen (unclassified) within each pollen diagram follows this section. Secondly, a more detailed inspection of the contributions of the different classes of deterioration and of various pollen taxa is presented in sections 4 and 5 for five of the pollen diagrams. A brief review of previous work on deteriorated pollen grains is given in section 3.

2. ANALYSIS OF THE CURVES OF TOTAL DETERIORATED POLLEN GRAINS

The total deteriorated pollen percentages, shown in the last curve in each pollen diagram, are based on the total land pollen counted. Records of deteriorated pollen grains were first made for the Cambusbeg site (Figs. 18 and 19). The records only commenced after a number of other levels had been counted where no note had been taken of the deteriorated category. There is thus only a partial representation of deterioration here. Nevertheless it became immediately apparent that the highest totals for deteriorated pollen grains occurred in the basal clay deposits. In addition, a clear pattern emerged: the totals were very high (greater than 50%) in zone Cla; this was followed by a gradual decrease throughout zones Clb and Clc to a relatively low value (less than 20%) in zone Cld; there was then a marked increase in totals to a peak (57%) at the base of zone Clf; thereafter totals declined again to the lowest consistent values in the diagram in zones Clg and Clh. A second marked increase occurs at the Clh/Cli boundary, which coincides with an emphatic decline in the number of Corylus pollen recorded.

A remarkably similar pattern was then found in the Tynaspirit 1 diagrams (Figs. 15 and 16). Here the totals are extremely high (up to 70%) in Tla, and then decline to a relatively low value (20%) in Tlc. This low value coincides with the base of the Lateglacial organic horizon. Totals then increase consistently to a peak of 58% at the top of zone Tld, and then decline to the lowest consistent values in the diagram (between 15% and 30%) in zones Tlf and Tlg. Again there is a second major increase at the zone Tlg/Tlh boundary which coincides with a marked reduction in

Corylus pollen totals.

Four basic features are found to be similar in both the Cambusbeg 1 and Tynaspirit 1 diagrams:

(a) high average values for total deteriorated pollen grains throughout the Lateglacial zones;

(b) a basic subdivision within the Lateglacial zones into two zones of very high percentages of deteriorated pollen grains, separated by relatively lower values that coincide with the pollen assemblage zone that immediately precedes the Loch Lomond Stadial zone; i.e. the Allerod equivalent

(c) the low values of deteriorated pollen grains that characterise the early Flandrian zones;

(d) the marked increase in the proportion of deteriorated pollen grains at a boundary where *Corylus* suddenly declines in value.

Part of this basic outline was again supported by the later analysis of Tynaspirit 2 (Fig. 17). Here the extremely high values characteristic of the lowermost spectra at Cambusbeg 1 and Tynaspirit 1 are not repeated, but there are generally decreasing values from zone T2a to zone T2c. The highest values of deteriorated pollen grains recorded are within the Loch Lomond Stadial zone T2d, and the lowest consistent values in the Flandrian zones T2f and T2g. The dominant *Corylus* zones are not included in pollen diagram Tynaspirit 2, and thus there is no support here for feature (d) listed above.

Data from Amulree 1 (Figs. 20 and 21) also agree with the generalised scheme outlined above. Thus values of 70% deteriorated pollen are recorded within the Lateglacial zones, and very low values (10% or less) are recorded throughout the early Flandrian zones Amle, Amlf, and Amlg. There is a slight rise in the proportion of deteriorated pollen grains at pollen zone boundary Amlg/Amlh where *Corylus* percentages begin to fluctuate and the percentage of Cyperaceae pollen rises markedly. A more significant increase in deteriorated pollen (from about 14% to about 30%) occurs at the Amlh/Amli boundary, where *Corylus* pollen totals decline from 91% to less than 30%.

Within the Lateglacial zones Am1a to Am1d the pattern is somewhat different from that of Tynaspirit 1, Tynaspirit 2 and Cambusbeg 1. The deteriorated pollen percentages gradually increase from 35% to a high of 70% from the base of Am1a to the top of Am1b. There is a decline but also marked fluctuation within Am1c, and totals more consistently increase in zone Am1d. The subdivision of the deteriorated pollen curve is not straightforward. With the exception of one level, 895 cm, the pattern is similar to other diagrams from level 950 cm. The pattern between 950 cm and the base has no equivalent.

There is some contrast in the deteriorated pollen curves of Amulree 1 and Amulree 2. Evidence from Amulree 2 is only available from a depth of 1070 cm (Fig. 22) yet a contrast is evident in the total amount of deteriorated pollen grains recorded, with lower percentages in general recorded at Amulree 2. Here the deteriorated pollen totals, though fluctuating slightly, generally decrease throughout zones Am2a to Am2e. Within zone Am2e there is a marked increase (from less than 15% to about 50%) which persists into zone Am2f. In the Flandrian zones Am2f (Upper) and Am2g, very low percentages of deteriorated pollen grains, generally less than 10%, are recorded.

There is no more evidence for developments within Lateglacial zones since the Mollands and Glenturret sites contain Flandrian sediments only. Within the Mollands diagram (Fig. 24) the early Flandrian zones Mob, Moc, and Mod are characterised by very low totals of deteriorated pollen grains, though in zone Mod they begin to rise gradually but consistently. The most prominent feature in this diagram is the sharp increase in deteriorated pollen percentages at the Mod/Moe pollen zone boundary. The total deteriorated pollen curve fluctuates greatly throughout zones Moe, Mof, and Mog, but the first major rise in its representation (from about 20% to 108%) coincides with the end of the Corylus dominance in the diagram. No causal relationship is advanced yet between these two factors in this or any of the previous diagrams, but it is the one point on which all the diagrams so far agree. This marked rise in the proportion of deteriorated pollen grains also coincides with other important features at Mollands: the marked increases in Salix and arboreal pollen, and in Filicales spores; the virtual exclusion of aquatic pollen; and the termination of significant phases of Equisetum, Gramineae, and Cyperaceae.

In Fig. 25 a detailed analysis of the Loch Lomond Stadial/Flandrian transition is given. There are high percentages of deteriorated pollen at the base of the diagram, with 40% being the highest value at the base of sub-zone MoaI. The percentages then decline throughout sub-zone MoaII. All the other subdivisions of zone Moa, and of zone Mob, are characterised by low percentages (10% or less) of deteriorated pollen, and these can therefore be equated with feature (c) outlined above.

Similarly, very low percentages of deteriorated pollen grains characterise zones Gla and Glb in the Glenturret diagram (Fig. 26). There is also a sharp rise in the proportion of deteriorated pollen grains at the Glb/Glc zone boundary which is coincident with

(i) a major decline in Corylus, though the first decline in Corylus from its dominance occurs in the lower part of zone Glb;
(ii) the end of a major Cyperaceae phase;
(iii) a dramatic rise in the percentages of Pteridophyte spores;
(iv) the virtual exclusion of aquatic pollen grains;
(v) a rise in arboreal pollen percentages.

Thus at Glenturret it is not the direct relationship with the Corylus pollen curve that is apparently important but, as at Mollands, a major rise in the Flandrian of deteriorated pollen percentages occurs at a point where there is evidence for over-representation of local taxa and for a fall in the water-table in the basin.

There are a number of consistent features that have been abstracted from the total deteriorated pollen curves for all of the diagrams presented above. It is possible to advance hypotheses on the derivation and the implications of the deteriorated pollen on this information alone. For instance, the hypothesis that the high values of deteriorated pollen grains within the Lateglacial zones are in some way related to soil disturbance, mass wastage, or increased run-off, or a combination of all three, due to the harsher environmental conditions suggested for this period, is one possibility. An explanation of the marked Flandrian rise in deteriorated pollen is more problematic.

Any hypothesis, however, must recognise the important distinction between chemical and physical deterioration, and must take into account the complicated background of the relationship of the deteriorated pollen to its final sedimentary position. Thus some of the deteriorated pollen grains may originate from deposits that have accumulated outside the basin and that were later eroded and transported to the basin by streams or percolating ground-waters. This would therefore involve the incorporation of pollen grains older than those grains that are contemporaneous with basin sediment accumulation. Further, deteriorated grains may derive from the redeposition of disturbed sediments from around the edge of the basin itself. Again, significant non-contemporaneity of pollen grains may result. A third derivation of deteriorated pollen grains might be the inwash of penecontemporaneous material from the local slopes around the basin, either through the action of streams or soil-wash and soil percolation. Fourthly, deterioration may be a result of post-depositional processes, such as oxidation of organic material in situ.

Because of these difficulties a much more detailed analysis is described in section 5 and discussed in section 6 for five pollen diagrams. Unfortunately time did not permit detailed recording and analysis of deteriorated pollen grains for all of the available pollen diagrams. The five frequency diagrams of deteriorated pollen (Figs. 28-32) give more insight into the possible relative importance of chemical and physical alteration at any particular level, and outline the different types of deterioration within separate taxa.

3. PREVIOUS LITERATURE ON THE ANALYSIS OF DETERIORATED POLLEN GRAINS

In a study of redeposited pollen in Late-Wisconsinan (Late Devensian) deposits from Minnesota, Cushing (1964) recognised two sources of redeposition. Redeposited pre-Quaternary microfossils were found to be derived mainly from fragments of Cretaceous rocks in the local glacial drift. Such grains are usually obvious in morphology and in the appearance of their surface texture, and thus they can be easily eliminated from the regional pollen diagram. Cushing noted that the majority of pre-Quaternary microfossils were "degraded", which is equated with the amorphous class employed by the author. His second source of redeposition was from the inwash of soil from the slopes surrounding the basin under study. This he termed penecontemporaneous redeposition, defined as "... derived from surface materials containing pollen that came from the plants also contributing to the atmospheric pollen rain during the time of deposition" (1964, p.1087). This type of redeposition was characterised by a high percentage of corroded pollen grains. Although Cushing in fact did not stress this point, it would appear that typically amorphous pollen are characteristic of fossil material that has been subject to deterioration over a long period of time. The implications of corroded pollen grains are discussed later.

Cushing was able to recognise the inclusion of penecontemporaneous redeposited pollen grains in basin deposits because of several litter horizons of organic detritus. These litter horizons, which produced sudden marked changes in the pollen curves, were found inter-stratified with silts and organic silts. He made three important conclusions concerning redeposited penecontemporaneous pollen:

(1) that each layer of litter, together with its content of pollen, was derived from a source local to the basin, and reflected a different local vegetation to that generally recorded in the respective pollen spectra;

(2) that the presence of marked fluctuations of a pollen type in spectra that contain penecontemporaneous redeposited pollen is good evidence that that pollen type indicates a taxon that was present near to the site;

(3) that penecontemporaneous redeposition may demonstrate the presence in the local flora of taxa whose pollen might otherwise be considered to derive from long-distance transport.

Cushing's paper is valuable, therefore, in demonstrating that analysis of deteriorated pollen can give useful information on plant communities that were local to the site under investigation. A contrast is suggested between large open basins, where almost all of the pollen would come from the atmospheric pollen rain, and small basins where it would be expected that pollen spectra would be heavily contaminated by penecontemporaneous redeposition which could then be used to reconstruct the local pollen communities near the site. Further, his study indicates possible conditions for deterioration:

> "Pollen deterioration is to some extent related to redeposition. At Andree Bog, corrosion, which perhaps results from attack on the exine by anaerobic bacteria, is characteristic of penecontemporaneous pollen. The degraded condition, which may result from physical abrasion or compression, is typical of the secondary pollen in the till" (1964, p.1087)

In a later paper (1967) Cushing claimed a close relationship between mode of preservation and lithology. Degraded (amorphous) pollen grains were found to be common in silt, crumpled pollen grains were dominant in organic deposits rich in algal remains (algal copropel), and corroded pollen grains were common in moss peat. Grichuk (1967) provided support for a close relationship between sediment type and mode of preservation. In a site in the Ob Basin he found an association of the highest counts of exotic or redeposited pollens and spores with the coarsest sediments, which he interpreted as a reflection of the intensity of erosion of nearby Oligocene sediments. Similarly Martin (1958) in a previous study in Pennsylvania had found an anomalous association of pollen of deciduous hardwoods with those of boreal elements in the same spectra within clays and sandy deposits. This he interpreted as indicating secondary redeposition.

More evidence of a strong relationship between lithology and type of deterioration of pollen is given in Birks' study (1970) of inwashed pollen spectra at a site on the Isle of Skye. The sediments he studied in detail were a series of moss bands inter-stratified with silts and sands. Pollen grains in the moss layers were largely corroded, which he attributed to aerial oxidation and microbial attack. Pollen grains in the silts and sands were often broken and degraded (amorphous), attributed to mechanical damage.

Almost all other available papers on redeposition and/or deterioration of pollen grains are concerned with pre-Quaternary derived pollens and spores (Heinonen, 1957; Davis, 1961; Phillips, 1972). There is very little available information on deteriorated pollen. Clearly one can easily make positive statements where there are clear stratigraphic indications of inwashed material (as, for instance, the moss layers studied by Birks, or the detritus zones studied by Cushing), but this is more difficult when basin deposits do not contain obvious sediment variations, as in the case in much of the Flandrian deposits described in this thesis. Another difficulty is the lack of experimental work on the causes of the different types of deterioration. Experimental work has largely concentrated on corrosion and oxidative effects (Sangster and Dale, 1961, 1964; Havinga, 1964), with a neglect of possible causes of mechanical deterioration. That corrosion is a chemical effect is readily acceptable, but both Cushing and Birks have assumed that degraded (amorphous) conditions indicate physical alteration of pollen grains. It is not possible at present to test the validity of this assumption.

That oxidation is the main cause of corrosion is accepted by most. What is not clear is the length of time it would take for corrosion to become noticeable after exposure to air and to microbial attack. Thus it might be a process that requires several tens of years, or even more, or it might be 'immediate', <u>i.e</u>. require only one or two years of exposure. Many authors had considered that the pollen exine would oxidise in a natural aerobic environment, but Havinga (1964) pointed out that this was never proved experimentally. In fact, experiments by Havinga showed that the oxidising effects were possibly not as great as had been assumed, and they indicated the sporopollenin content of pollen grains and spores to be corrosion-resistant in aerobic conditions. Further, experimentation on the susceptibility of Pinus and Populus pollen to bacterial activity again resulted in few traces of corrosion. If, however, pollen was first oxidised and then inoculated with bacteria and fungi, then the corrosion effect was found to be severe and developed rapidly.

Königsson (1969), in a study of the degree of destruction of pollen grains from sediments in the Great Alvar Lake in Sweden, concluded that corrosion effects could become noticeable in some pollen types in one or a few summer seasons. Transport factors were the important variables. What he termed the reflotation process, where pollen is first captured on twigs and branches during the flowering period and then released and spread again later during the year, may provide a sufficient period and the necessary conditions for corrosion to occur. Tauber's work (1967) concerning the different modes of pollen transfer after release, indicates that a considerable proportion is captured on branches, twigs, stems and leaves in a "filtration" process, and though some of this is re-released almost immediately a large proportion remains adhering to vegetation surfaces providing the time-period required for deterioration during reflotation. Königsson suggested that "... a combination of long distant transport and the refloatation effect may yield enough time for the oxidation of ... Alnus and Corylus pollen so that bacterial and fungial attacks upon the pollen will result in corrosion when the pollen is deposited in the central telmatic fen communities of the Alvar Lake" (1969, p.164).

Another important factor stressed by Königsson (1969) is that different degrees of preservation in different pollen types are a result of different transport factors. Thus, for instance, the greater degree of destruction in Alnus and Corylus pollen, when compared with pollen of Betula and Gramineae, was possibly explained by the fact that in the Alvar Lake Alnus and Corylus pollen had a regional or long-distant source, whereas Betula and Gramineae pollen emanated from local source communities. When this analysis is compared with Cushing's (1964) conclusions described above, then the analysis of curves of corroded pollen becomes extremely difficult. Whereas Königsson suggests that some regional components will tend to show signs of corrosion due to their exposure to oxidation and microbial attack during air-transport, Cushing claimed that pollen from local communities are corroded as a result of deposition on soil or humus around a basin prior to being washed into the basin some time later.

In addition to the problem of differential preservation as a result of different transport factors, an equally important factor is differential preservation of pollen due to differential resistance to particular decay or disintegration processes. Though there is very little work indeed on this factor, it is often included as a warning in papers on methods and problems in pollen analysis. Cushing (1967) found indications of differential preservation of pollen in a study of fairly limited taxa from lake deposits in Minnesota. Some detailed results were given especially for _Populus_ pollen. It had been previously supposed that _Populus_ pollen is the least likely tree-pollen type to be preserved in sediments (Lichti-Federovich and Ritchie, 1965). One hypothesis advanced was that since the Populus exine is very thin and the ektexine discontinuous, then _Populus_ pollen might disappear from sediments in time by fragmenting into scraps of exine too small to be recovered or identified. Cushing's paper supported the claim that _Populus_ pollen is extremely poorly preserved, but he pointed out that _Populus_ grains seemed to be less commonly broken than other pollen types in the Minnesota sediments, and his observations suggested that crumpling is more likely related to the poor recovery of _Populus_ than breakage. Not only is it more likely but it is much more severe, resulting in difficulties of recognising _Populus_ pollen even as pollen grains. Cushing also found a degree of crumpling in _Ulmus_ and Gramineae grains, and concluded that "... it seems probable that the same process responsible for the crumpling and thinning of _Populus_ exines ...

acted upon all pollen types but that susceptibility to the process varies among types" (1967, p.100).

Cushing's work concentrated on crumpling effects, but it seems extremely likely that there is differential resistance in pollen types to all the possible chemical and physical alteration processes. Faegri and Iversen (1964) quote differential destruction of pollen grains as one of the classical errors in pollen analysis:

> "As the composition of the exine and its resistance to corrosion differ from one group to the next, it goes without saying that if pollen grains are subject to any notable degree of corrosion during fossilisation or after, the composition of the pollen flora will change, the more resistant types will appear to accumulate owing to the disappearance of their counterparts, the less resistant pollen grains" (p.120).

Faegri and Iversen suggest that samples should be discarded if more than half the sum of the pollen grains of deciduous trees show signs of corrosion. In any case, where deterioration is a marked feature of pollen diagrams and the samples are not discarded (as in some of the levels of diagrams in this thesis), the result of differential destruction as outlined by Faegri and Iversen is an important factor to bear in mind when comparing local pollen assemblage zones. Marked differences may occur not only through differences in local pollen rain, but also possibly due to differential preservation of pollen types within different sediments, or in similar sediments that have experienced different post-depositional histories.

Available research on deteriorated pollen has achieved little more than a rudimentary understanding of the complicated variables involved. The main causes or sources of deterioration appear to be:-

(a) penecontemporaneous redeposition from soils and humus on slopes local to the basin;

(b) intra-basinal non-contemporaneous redeposition, involving erosion of deposits from the edge of the basin possibly due to a lowering of local water-table;

(c) deterioration of contemporaneous or fresh pollen grains as a result of the reflotation process;

(d) redeposition of pollen from deposits that have accumulated outside the basin:

(i) penecontemporaneous, by the action of streams and soil-wash on penecontemporaneous soils or deposits;

(ii) derived pollen, from older deposits, possibly including erosion of pre-Late Quaternary and even pre-Quaternary deposits;

(e) pressure due to accumulating sediments within the basin, resulting in physical damage to pollen grains;

(f) post-depositional in situ chemical changes, such as oxidation due to a lowered water-table.

One factor that has not so far been studied in detail is the effect of macrofauna that ingest pollen grains. Pollen grains are ingested by lake-dwelling animals, particularly by burrowing animals at the under-water surface, along with other deposited organic materials. Despite their highly resistant exines, it is unlikely that pollen grains survive the digestion processes of, for instance, the nematode worm without some physical or chemical modifications. In addition, microfauna and microflora may attack pollen grains as they float on the lake surface or as they sink through the water to the lake floor. These processes, if significant, would vary with the trophic state and the acidity of lake waters, as indeed faunal populations are influenced by the degree of eutrophication. Modifications as a result of microfaunal and macrofaunal activity would also occur in the soils and the streams of the surrounding catchment, prior to deposition in the lake.

Figure 27 attempts to show diagrammatically the possible sources of deterioration that could result at any one level within basin deposits over a period of time. It is essentially a static diagram. If one considers the dynamic aspects of the diagram then a very complicated picture emerges.

The results of these and other possible factors can be very serious in the analyses of pollen curves and thus in palaeoecological reconstructions. An indication of the importance of redeposition is given in Hibbert,

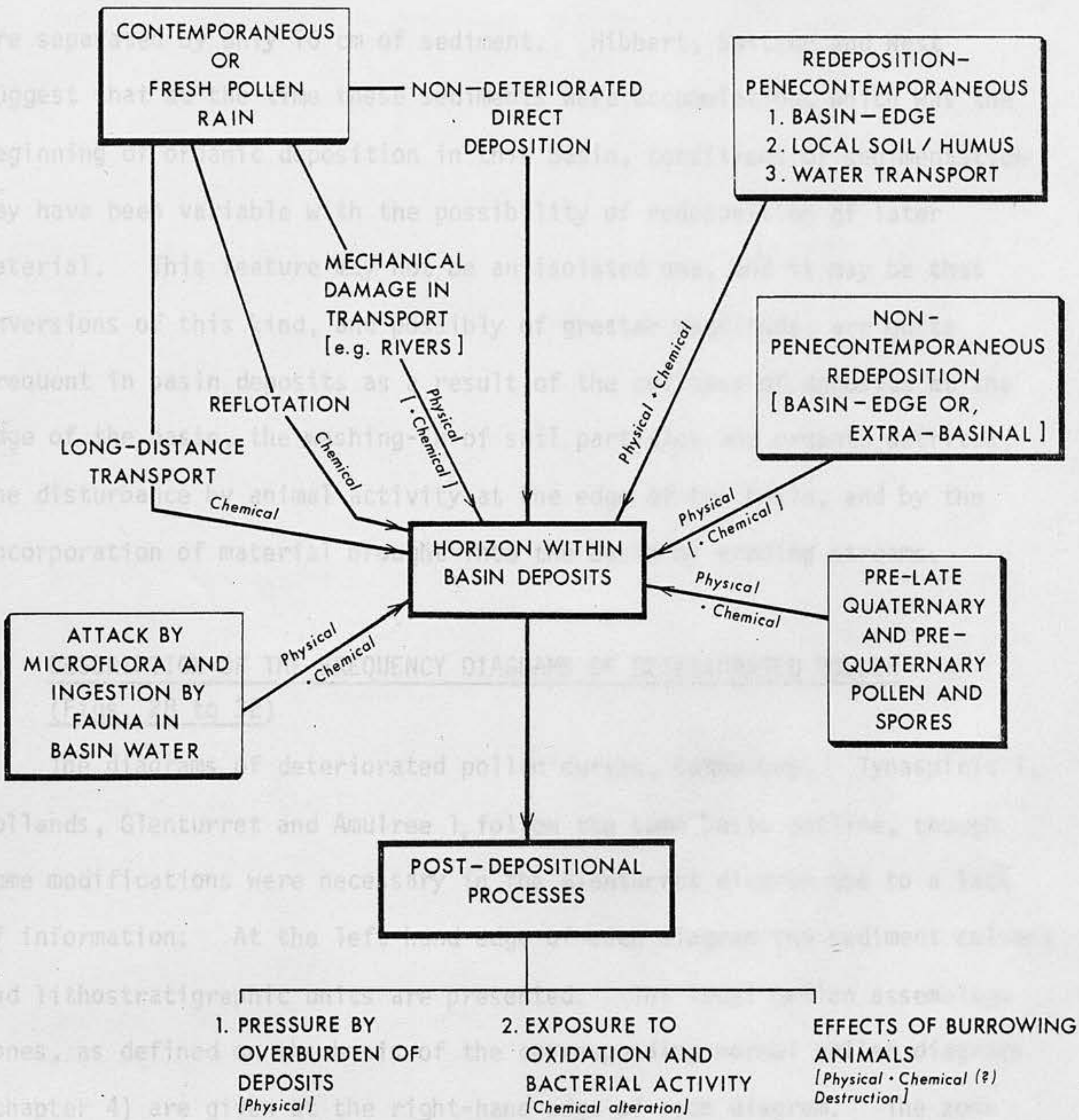


FIGURE 27 Possible sources of deteriorated pollen grains and spores at any single horizon within terrestrial basin deposits.

Switsur and West's recent attempt to establish chronozones in Lancashire (1971). Of the 16 Flandrian radiocarbon dates they presented, the bottom two were found to be inverted in age. Thus the basal date was 9,508 ± 200 B.P., and the next above 9,798 ± 200 B.P. There were no signs of a hiatus in the sediments, or of redeposition, and the two dates are separated by only 10 cm of sediment. Hibbert, Switsur and West suggest that at the time these sediments were accumulating, which was the beginning of organic deposition in this basin, conditions of sedimentation may have been variable with the possibility of redeposition of later material. This feature may not be an isolated one, and it may be that inversions of this kind, and possibly of greater magnitude, are quite frequent in basin deposits as a result of the collapse of deposits at the edge of the basin, the washing-in of soil particles and organic detritus, the disturbance by animal activity at the edge of the basin, and by the incorporation of material brought into the basin by eroding streams.

4. DESCRIPTION OF THE FREQUENCY DIAGRAMS OF DETERIORATED POLLEN (Figs. 28 to 32)

The diagrams of deteriorated pollen curves, Cambusbeg, Tynaspirit 1, Mollands, Glenturret and Amulree 1, follow the same basic outline, though some modifications were necessary in the Glenturret diagram due to a lack of information. At the left-hand edge of each diagram the sediment columns and lithostratigraphic units are presented. The local pollen assemblage zones, as defined on the basis of the corresponding normal pollen diagrams (chapter 4) are given at the right-hand edge of each diagram. The zone boundaries drawn across each diagram of deteriorated pollen are thus not derived from changes in the deteriorated pollen curves, but are the original pollen assemblage zone boundaries reproduced for comparisons.

Four basic abstractions from the deteriorated pollen counts are represented in a number of sections itemised at the base of each diagram:

Section A: The total deteriorated pollen, given as a percentage of total land pollen, is reproduced here. (This curve is also given in the normal pollen diagrams.)

Section B: This section records the varying representation of each class of deterioration. Corroded, amorphous, broken and crumpled pollen are each shown as a percentage of total deteriorated pollen.

Section C: Some of the more prominent contributors to the deteriorated pollen totals are represented here by two curves. Each taxon is shown as a percentage of (i) the total deteriorated pollen recorded (recognisable/determinable plus indeterminable) and (ii) the total recognisable deteriorated pollen. Curves for (i) are shown as black shaded curves, and (ii) is represented by the accompanying lined frequency curve.

Sections D, E, etc. For a few of the most notable taxa in the deteriorated pollen totals frequency curves are given that are based on the sum of the taxon itself, i.e. the sum of the deteriorated plus non-deteriorated grains of that particular taxon at each level. Thus, for instance, deteriorated Betula pollen totals are shown as percentages of the total number of deteriorated plus non-deteriorated Betula pollen recorded. For some the total deteriorated pollen curve is subdivided to show the varying proportions of each class of deterioration for that taxon.

Section B is designed to reveal the possible processes that have taken place at different levels, for instance through the relationship of different types of deterioration to lithology, or to major changes in local pollen assemblages. Section C illustrates the varying proportions of those taxa making the most significant contributions to the overall deteriorated pollen totals. However, sections D, E, etc. are necessary for two main reasons:

1. A taxon such as Betula may appear as a significant proportion in section C simply because the total Betula influx (deteriorated plus non-deteriorated) is high. Thus, for instance, if Betula accounts for 150 pollen grains in the total land pollen sum of which only 10% is deteriorated, then this would result in 15 Betula deteriorated pollen grains being included in the total deteriorated pollen count. On the other hand, a count of, say, 30 Salix grains of which 50% are deteriorated, would similarly only result in 15 deteriorated Salix pollen grains being included in the total deteriorated pollen count.
2. Where the total deteriorated pollen totals are low, curves in section C can appear misleadingly prominent, as for instance in zone Am1g (Figs. 21 and 30).

Clearly then, it is important to know the proportion of major taxa in the diagrams that are corroded, or amorphous, and so on. This would be a crucial factor where, for instance, some estimation of the redeposition process is required (see section 5). However, since there is such a wide variation in the totals of deteriorated pollen recorded for each taxon, the basic sums are given first in sections D, E, etc. This makes it possible to gauge the importance of parts of each curve against the total number of that taxon recorded. A deterioration ratio of 50% or greater may or may not be significant where less than 10 grains in total were recorded, depending on the taxon involved. Extremely high percentages are represented by figures enclosed by dashed lines in order to condense the diagrams. It was also considered unrealistic to include portions of curves where basic sums are exceedingly low, as, for instance, with Alnus (section E) in zones Cla - Clf in the Cambusbeg diagram (Fig. 18).

Some modification to the outline of the deteriorated pollen diagrams was necessary for the Glenturret diagram (Fig. 32) where less information was available. In section C each taxon is shown only as a percentage of the total deteriorated pollen. No percentages of the total recognisable deteriorated pollen grains are supplied. In sections D to I only the basic sums and the curve of total deteriorated grains for each taxon are supplied. No information is available for Glenturret on the representation of the different classes of deteriorated pollen within each taxon.

5. ANALYSIS OF THE DIAGRAMS OF DETERIORATED POLLEN (Figs. 28 to 32)

A. TYNASPIRIT 1 (Fig. 28)

Section A. (see part 2, this chapter).

Section B. This part of the diagram shows a strong contrast in types of deterioration between the mainly minerogenic basal deposits and the Flandrian organic deposits. Throughout zones Tla to Tlf the broken and crumpled classes together account for 60% or more of the deterioration totals. Percentages of corroded pollen are low (10%

or less) throughout these zones with the exception of two slight expansions in zones T1a and T1e. Totals of amorphous pollen fluctuate, with little apparent pattern, whereas crumpled grains increase gradually but consistently from about 20% to 40% throughout zones T1a - T1f.

At the T1f/T1g boundary there is a marked change in deterioration type, though the change begins within the upper part of zone T1f. Corroded and amorphous grains, with corroded pollen being the dominant class, together account for about 70% or over of the total deteriorated throughout zones T1g and T1h. The corroded class continuously increases in representation throughout these upper zones, finally accounting for 50% of total deteriorated grains in zone T1h. Amorphous and broken pollen grains maintain fairly consistent values throughout T1g and T1h, but the proportion of crumpled grains decreases consistently throughout, and in the upper part of T1h only accounts for less than 5% of the total.

Section C. The main contributors in the basal zones T1a - T1f are Betula, Gramineae, Cyperaceae and Juniperus (T1a - T1e only). Emphasis is placed upon the order of representation of different taxa in these zones. Thus a high representation of Cyperaceae (with less marked Betula representation) in zone T1a is followed in zones T1b and T1c by Rumex and then Gramineae. In zone T1d Betula is important with Cyperaceae becoming the dominant taxon towards the upper limit of this zone. A marked increase in Juniperus in zone T1e is followed in zone T1f by a dominance of Gramineae pollen and Filicales spores, with Betula also important.

In those zones where the corroded class is dominant Betula and Corylus are the main contributors. Betula increases from 14% to over 40% throughout zones T1f - T1h, and Corylus becomes significant at the T1f/T1g boundary, but decreases thereafter from 40% to about 10%.

Section D. The curve for total deteriorated *Betula* pollen grains (as a percentage of total *Betula* pollen) is almost identical in general outline to the curve for total deteriorated pollen (section A). Thus 40% of *Betula* grains are deteriorated in zone T1a, and about 50% in the upper part of T1d. The percentages for deteriorated *Betula* pollen grains are low in zones T1c, T1f and T1g, but increase markedly in zone T1h. These fluctuations do not follow the pattern of *Betula* representation in the normal pollen diagrams (Figs. 15 and 16). Most of the deterioration is in the corroded and amorphous classes. Corrosion is dominant in zones T1a, T1e, and T1h, and there is an accompanying marked increase in amorphous grains in zones T1d and T1e.

Section E. The numbers of *Corylus* grains recorded in zones T1a to T1e are very low, and much of the pollen count recorded here is deteriorated. Almost all of the deterioration is in the corroded or amorphous categories. *Corylus* pollen is recorded only in the minerogenic deposits (lithostratigraphic units 2 and 5, Fig. 15). In zones T1f and T1g, where the numbers of *Corylus* pollen grains are exceedingly high, deteriorated *Corylus* totals are very low (less than 10%). A sharp increase occurs at the T1g/T1h boundary, and this occurs almost exclusively in the corroded and amorphous classes.

Section F. All four categories of deterioration are recorded here, but broken and crumpled grains dominate. Deterioration percentages are high but fluctuate (13% to 35%) throughout zones T1a - T1f, and remain low in T1g with a slight increase in T1h. Of note are the lower total deteriorated Gramineae totals in zones T1b and T1c, and the marked peak in corroded Gramineae grains recorded in zone T1h.

Section G. As with *Betula* in section D, the total deteriorated Cyperaceae frequencies are highest in zones T1a and T1d/T1e, with generally lower totals in T1b and T1c (and in the case of Cyperaceae in the lower levels of Tld). Almost all of the deteriorated Cyperaceae grains are, however, in the broken and crumpled classes. Similarly, when the total Cyperaceae deteriorated pollen grains increases in zones Tlg (upper) and Tlh, it is almost exclusively in the broken category.

(ii) Interpretation

The very high totals of deteriorated pollen grains that coincide with the minerogenic deposits at Tynaspirit 1 (section A, Fig. 28) are related to physical processes of alteration, as it is mainly broken and crumpled deteriorated grains that are recorded. The hypothesis that minerogenic deposition results from harsher climatic conditions resulting in a thinning of vegetation cover, a disturbance of soil, and increased soil wash (possibly also related to an increase in run-off) has been advanced several times in this thesis. Such factors could also explain increased percentages of physically deteriorated pollen grains. If the physical deterioration was due solely to compaction within the basal sediments, it would be expected that the percentages of physically deteriorated pollen would remain high throughout the basal zones Tla to Tlf. The fact that these frequencies vary in accordance with major lithological and vegetational changes suggests that they are directly related to variations in environmental conditions.

The question arises as to whether this physical deterioration relates to contemporaneous, penecontemporaneous, or non-contemporaneous (redeposited) pollen. If the deteriorated pollen grains accumulating at these levels are contemporaneous or penecontemporaneous with the non-deteriorated grains, then one would expect parallelism between the pollen curves in the normal pollen diagrams (Figs. 15 and 16) and the deteriorated pollen curves in section C (Fig. 28). That is, the pollen grains most likely to be represented would be those that are most common in the local vegetation. This inference, however, does have a serious drawback in that it ignores the effects of differential resistance to physical destruction in different pollen types. In comparing section C, Fig. 28, with Figs. 15 and 16, there are good parallel developments in the curves for Gramineae, Cyperaceae, Rumex, Juniperus and Salix in zones Tla to Tlf. However, in the curves for Betula and Corylus there are two important areas of conflict. In zone Tlc, where there is a marked increase in Betula pollen, deteriorated Betula pollen grains account for about 30% of the total. In zone Tld, where there is a marked reduction in Betula pollen, the deteriorated Betula frequencies increase. This may possibly reflect the washing of older material into the basin. Thus Betula pollen, which may have accumulated in local soils during the relatively mild (Interstadial) Tlc phase, may have been washed into the basin with the destruction of soils during the Loch Lomond Stadial zone Tld. Section D shows that over 40% of the total Betula pollen recorded in this latter zone are deteriorated, with much of the deterioration accounted for in the amorphous category. There is some difficulty in interpreting variations in the amorphous category (see this chapter, section 3).

It is difficult to interpret the representation of deteriorated Corylus pollen grains in zones Tla to Tle. It was earlier assumed that the Corylus pollen grains recorded in these zones were a result of contamination through contact with younger organic deposits that had adhered to the Hiller sampling chamber. However, if this were so, it is difficult to account for the high representation of deteriorated Corylus pollen since one would expect the source of the contamination to be the Corylus-dominated zone Tlg, where deteriorated grains account for a very small percentage of the total. It is likely that the non-deteriorated grains do represent contamination in the manner suggested, but that the deteriorated Corylus grains recorded here have been misidentified. It is often difficult to separate non-deteriorated grains of Betula and Corylus in minerogenic samples, especially where a solidifying medium is employed, and thus the likelihood of misidentification is greatly increased where one is dealing with corroded and amorphous grains (Fig. 28, section E). It is probable that many of the corroded and amorphous Corylus grains recorded in zones Tla, Tld and Tle are in fact Betula grains.

A number of explanations could be advanced for the great increase in the corroded pollen representations in zones Tlg and Tlh. The first major problem is to decide whether this represents the corrosion of pollen prior to sedimentation in the basin or whether it relates to post-depositional oxidation of sediments. Four features indicate the former explanation to be the more likely:

(a) There are no indications of colour change in the peat sediments (lithostratigraphic unit 7, Fig. 16) that would indicate oxidation. The peat between 540 cm and 430 cm is a black fine detritus throughout.

(b) Though there are differential susceptibilities to oxidation it might be expected that the majority of taxa would show severe signs of corrosion after exposure to aeration. The corrosion in zones Tlg and Tlh is selective. The author has examined near-surface peat samples from Auchencorth Moss (Midlothian) and Tynaspirit, and from an exposed peat section at Wrink Law near Longformacus (Berwickshire), and found in each case almost all of the pollen to be corroded or amorphous. (There are, however, no statistical data available for these samples.)

(c) There is a continuous representation of aquatic pollen in zones Tlg and Tlh. This would not, however, invalidate intermittent or periodic lowering of the water table which could also result in corrosion of pollen.

(d) The increased representation of broken pollen grains of Betula and Cyperaceae, and the continued representation of broken Gramineae pollen grains, suggests that material was still being washed into the basin during zones Tlg and Tlh, resulting in the physical deterioration of pollen grains. The proportions of broken and crumpled grains may be greatly under-represented in zones Tlg and Tlh as a result of the hierarchial classification employed.

The Tynaspirit diagram of deteriorated pollen frequencies is interpreted as showing mainly contemporaneous or penecontemporaneous deposition of disturbed soils and organic detritus, this being particularly significant in zones T1a and T1d. The milder conditions of zone T1c are reflected in the lower deteriorated pollen totals. A greater degree of non-contemporaneity in deposition may have occurred in zone T1d, where the increased frequencies of corroded and amorphous pollen grains, in addition to the increase in physically deteriorated pollen grains, indicate disturbance of soils that had developed in the milder Lateglacial Interstadial zones. The increased corroded pollen frequencies in zones T1g and T1h are not thought to result from post-depositional in situ oxidation. Whether they result from the washing-in of oxidised soils from the local slopes or from pollen that had been subjected to the effects of reflotation cannot be decided on the evidence of this diagram alone.

B. CAMBUSBEG (Fig. 29)

(i) Description

Section A. (see part 2, this chapter).

Section B. In contrast with the deposits of Tynaspirit 1 there is a much higher representation of corroded pollen in the basal layers at Cambusbeg. The highest frequencies for broken and crumpled pollen grains also occur in the basal layers, particularly within the clay deposits of lithostratigraphic unit 3. The corroded class is much reduced in zones C1b and C1c, but increases consistently and significantly thereafter to a maximum in excess of 70% at the end of zone C1e. There are three major increases in broken and crumpled grains, in zones C1b and C1c, zones C1f and C1g (lower), and in zone C1h. Corroded grains are highest in frequency in zone C1g (80%) and gradually but consistently decline in percentage throughout the upper spectra of the diagram. The amorphous category accounts for a very small proportion in the basal zones C1a to C1e, but increases significantly (10% to 20%) in the Flandrian spectra.

Section C. Gramineae pollen grains are dominant in the deteriorated pollen of the basal deposits, with Betula, Juniperus, Cyperaceae, herbaceous pollen and Filicales spores also important. (Corylus is not discussed here as most of the representation of this taxon is considered to be a result of contamination or possibly mis-identification - see discussion of Tynaspirit 1 above.) With the exception of the Cyperaceae curve the trends of the curves in section C correspond with the major fluctuations in the normal pollen diagram (Figs. 18 and 19).

Zone C1g is dominated by the contribution of Betula deteriorated pollen grains, and in zone C1h there are marked increases in the representations of Alnus, Corylus, Gramineae and Cyperaceae deteriorated pollen. Alnus is particularly interesting here, as it is significant in the deteriorated pollen diagram yet is only minor in the normal pollen diagram (Fig. 19).

Sections D - I

(a) Basal zones C1a - C1f

Deteriorated Juniperus pollen and deteriorated Betula pollen increase significantly in zones C1d and C1e, the latter zone being equated with the Loch Lomond Stadial period. Corrosion is the major class of deterioration of Betula and Juniperus grains in these zones. Much of the Alnus pollen recorded in the basal zones is deteriorated, where again corrosion is the dominant class of deterioration, and this is true to a lesser extent of Corylus. There is little discernible pattern in the Gramineae and Cyperaceae curves (sections H and I) except for the marked increase in both in zone C1c.

(b) Zone C1g

Two factors are significant in this zone. Firstly, the zone is almost completely dominated by Betula grains, but as section D shows this does not indicate major deterioration within the Betula pollen influx. Secondly, there is a sharp decline in the frequencies of Cyperaceae deteriorated grains, though Cyperaceae continues to be an important taxon in the normal pollen diagram.

(c) Zones Clh and Cli

The most significant feature in this part of the diagram is the high frequency of deteriorated Alnus grains in zone Clh. Where the number of Alnus pollen grains recorded is relatively high (lower part of Clh and the Clh/Cli boundary) the amount of deterioration is relatively low (30% or less). Where the basic sum is low most of the Alnus grains recorded are deteriorated (as much as 75%). Most of the deterioration of Alnus grains is in the corroded and amorphous classes. At the Clh/Cli boundary Alnus deterioration percentages decline, but there are marked increases in the deterioration curves for Betula, Corylus, Gramineae and Cyperaceae grains. Though there is mainly an increase in corroded pollen, a significant proportion is also broken grains without any indications of corrosion.

(ii) Interpretation

The basal deposits at Cambusbeg are difficult to interpret in terms of their deteriorated pollen content because of the known contamination and deformation resulting from the use of the Hiller sampler (see chapters 4 and 5). Figure 29 is generally interpreted as indicating contemporaneous or penecontemporaneous deposition of deteriorated pollen transported to the basin by soil-water percolation, sheet-wash, or stream activity. The increased Cyperaceae and Gramineae percentages in zone Clc (section C), and the increase of corroded Juniperus and Betula grains in zones Cld and Cle (sections G and D respectively) could indicate the washing-in of soils with the harsher climatic conditions of the Loch Lomond Stadial. Juniperus pollen grains are not thought to be subject to long-distance transport (Vasari and Vasari, 1968), and the presence of corroded Juniperus pollen possibly indicates a source from local soils rather than indicating grains that have been subject to reflotation processes. The presence of Alnus and Corylus pollen in the basal zones are regarded as definite signs of contamination. Although badly corroded, there is little doubt about the identification of Alnus grains, and many of the Corylus grains recorded in the basal deposits were not deteriorated.

Deposits of zone Clg appear to have accumulated in a period of minimal deterioration activity, either by chemical or physical processes. There are very low deteriorated pollen frequencies, and most of these consist of Betula pollen which could represent long-distance transfer and thus deterioration by reflotation. Also there are no deteriorated Cyperaceae grains recorded in this zone. This taxon was present in the local vegetation (Fig. 19) and the pollen exine is very easily ruptured.

Following the low totals in zone Clg there are several features that indicate an increase in the amount of surface or basin-edge deposits being washed into, or collapsing into, the basin:

1. There are a number of thin silt and sand horizons within the dystrophic Flandrian deposits (lithostratigraphic units 6, 8, 10, 12 and 14). Pollen samples from lithostratigraphic units 6 and 8 did not show significant differences in the amounts of deteriorated pollen grains from those recorded in lithostratigraphic units 5, 7 and 9. Thus the presence of minerogenic deposits does not automatically result in an increase in the amount of deteriorated pollen, and the Flandrian minerogenic deposits contrast somewhat with the basal pre-Flandrian minerogenic deposits.

2. There is an increase in the percentage of deteriorated pollen grains, particularly at the Clh/Cli boundary, where the proportion of corroded pollen is decreasing. This does not support the hypothesis that the increase in deteriorated pollen at the Clh/Cli boundary relates to post-depositional oxidation due, for instance, to a lowered water-table.

3. The presence of aquatic pollen throughout and the nature of the deposits (soft organic muds) suggest the origin of corrosion to be extra-basinal, prior to deposition, and that the basin continuously contained a lake.

4. The increased proportions of broken grains of Alnus, Gramineae and Cyperaceae (sections E, H and I, zones Clh and Cli) suggest physical deterioration, presumably caused by abrasion during transport.

An alternative explanation could be that the water-table at Cambusbeg was lowered, particularly at the Clh/Cli boundary, which resulted in the collapse of unconsolidated sediments from the edge of the basin. One would then expect a much greater representation of Corylus pollen in zone Cli, since the lower deposits of Clh are so dominated by this pollen type. Also it is difficult to see by what mechanism pollen grains would be physically deteriorated as a result of this process. The increased frequencies of physical deterioration are interpreted as indicating transportation by water prior to deposition. However, there is a serious drawback in the interpretation of frequencies of broken and crumpled pollen grains in section B. Increased percentages of broken and crumpled grains do not necessarily imply real or absolute increases since under the hierarchial classification system employed in this thesis their totals are so dependent on the relative proportions of corroded or amorphous grains. Nevertheless the very presence of significant amounts of broken and crumpled grains implies physical effects that would not normally be expected in air transport and direct sedimentation. Their representation is thus interpreted as surface transport prior to sedimentation within the basin. Chemical and physical deterioration due to digestion by animals has been considered, but this is thought to be unlikely at Cambusbeg where the dystrophic sediments indicate exceedingly base-poor (low nutrient input) conditions, with pollen grains almost the only recognisable organic remains. Such conditions would have restricted animal activity in this basin.

The Alnus curve in section E, zones Clh and Cli, is of particular interest. Though low totals of Alnus pollen grains are recorded in zones Clh and Cli (it fluctuates but is of minor importance in the arboreal pollen totals of Fig. 19), much of this is deteriorated, mainly corroded or amorphous in nature. This cannot be accounted for by redeposition of basin-edge deposits as there is no dominant Alnus phase in earlier deposits. Nor can it be due to lowered water levels at this site, for reasons given above. It would seem to indicate either the washing-in of Alnus pollen from local slopes or the long-distance transport of Alnus grains leading to chemical alteration during the reflotation process.

C. AMULREE 1 (Fig. 30)

(i) Description

Section A. (see part 2, this chapter).

Section B. Broken pollen grains are predominant throughout this diagram, though frequencies of crumpled grains are also high in the basal minerogenic layers. Broken and crumpled grains together account for between 65% and 90% of the total deteriorated pollen throughout lithostratigraphic units 1 to 9. Crumpled grains account for over 30% of the total towards the base of the diagram, but gradually and consistently decrease throughout the diagram. Amorphous grains are more common than corroded grains in the basal deposits, but a significant increase in corroded pollen grains occurs in the Loch Lomond Stadial zone Amld.

In the Flandrian organic deposits broken and crumpled grains continue to be important, but amorphous grains increase significantly in zone Amlg, and corroded grains markedly increase at the Amlh/Amli boundary. Both corroded and crumpled categories decline throughout zones Amlj to Amlm to become insignificant in the diagram.

There is a strong relationship between lithology and the varying proportions of the different classes of deterioration. In the basal minerogenic layers crumpled and broken grains are dominant, with amorphous grains accounting for 15%-20% of the totals (lithostratigraphic units 1 - 9). Where the lithology changes to peat (lithostratigraphic unit 10) the broken category increases its dominance at the expense of crumpled and amorphous pollen. The change to Sphagnum and sedge peat (lithostratigraphic unit 11) coincides with increased representations of corroded and amorphous grains.

Section C. The dominant taxa in the basal zones Am1a to Am1e are herbaceous taxa with, to a lesser extent, Betula. The basal zone Am1a has additional important frequencies of Pinus, Salix, Erica and Empetrum. All of the curves (in zones Am1a to Am1e) of section C parallel the major changes of the corresponding curves in the normal pollen diagram (Fig. 20), though there are some differences in detail. Most important in the Flandrian zones are Betula and Corylus, with secondarily Cyperaceae and Pinus.

Section D. The proportion of deteriorated Betula grains increases consistently throughout zones Am1a to Am1d, interrupted however by marked reductions in zone Am1c. The highest percentages of Betula occur in zone Am1d and here, as in the Loch Lomond Stadial zones of Tynaspirit and Cambusbeg, there is a marked peak in corroded Betula pollen. In the Flandrian deposits deteriorated Betula grains account for a relatively small proportion of the total Betula influx, but there is an increase in zone Am1h and throughout zones Am1h to Am1m the percentages fluctuate between 12% and 30%. Broken grains account for the largest proportion of deteriorated Betula pollen throughout the Flandrian assemblage zones.

Section E. Deteriorated Corylus pollen grains are absent from the Lateglacial pollen zones, and they form an insignificant proportion of the total Corylus influx in the Corylus-dominated zone Am1g. A significant increase in the proportion of deteriorated Corylus pollen occurs at the end of the main Corylus phase, at pollen zone boundary Am1h/Am1i. This includes corroded grains in zones Am1i and Am1j, and broken and amorphous grains throughout zones Am1i - Am1m.

Section F. Throughout the diagram the deteriorated Gramineae pollen grains are mainly of the broken and crumpled categories. There are few noticeable points concerning the curves in this section except that the total deteriorated Gramineae pollen curve appears to conform to the Gramineae curve in the normal pollen diagram (Figs. 20 and 21), and that there is significant representation of Gramineae grains in zones Amlj, Amll and Amlm.

Section G. In the basal zones Amla to Amle the total deteriorated Cyperaceae pollen curve conforms to major changes in the Cyperaceae curve of the normal pollen diagram. However, the percentages remain very low (12% to 15% in zones Amlf and Amlg, and less than 10% in higher zones) in the Flandrian zones, even where the relative percentages for Cyperaceae are exceedingly high in the pollen assemblages. Broken and crumpled grains of Cyperaceae are dominant.

(ii) Interpretation

The deteriorated pollen from the Lateglacial clays at Amulree are interpreted as having been derived mainly from soil litter, humus, or other surface material washed into the Amulree basin. An important indicator here is the curve for deteriorated Betula grains (section D). The total deteriorated Betula pollen curve increases consistently throughout zones Amla and Amlb, decreases in zone Amlc, and achieves its highest totals in Amld. This is consistent with the hypothesis that an early immature soil and sparse vegetation cover in zones Amla and Amlb gave way to a more mature phase in Amlc, which reduced the rate of erosion of surface materials. The development of a Lateglacial Interstadial soil which was later disturbed or partially destroyed in the Loch Lomond Stadial zone Amld is consistent with the increase of deteriorated Betula pollen frequencies, and with the isolated corroded Betula pollen phase that occur in this zone. A comparison of section D of Fig. 30 with the Betula curve in Fig. 20 does not support the hypothesis that corrosion in the Lateglacial zones is due to long-distance transport and reflotation, as one might then expect the strongest representations of corroded Betula grains to coincide with the overall increased Betula percentages. This pattern for deteriorated Betula grains at Amulree is similar to those described for Tynaspirit 1 and Cambusbeg (above), and this therefore is added support for a Lateglacial interpretation of the Amulree basal deposits.

In zones Amlf to Amlh there are very low totals of deteriorated pollen grains coincident with the dry, compact peat of lithostratigraphic unit 10. The high percentages of broken and crumpled grains may reflect compaction in the sediments or the continued washing-in of pollen grains, but this involves only small frequencies of deteriorated grains. With the lithological change to a loose, wet peat, rich in macrofossils (lithostratigraphic unit 11) there is a marked expansion of the total deteriorated pollen curve and changes in the proportions of the different deterioration classes. This boundary, pollen zone boundary Amlg/Amlh, also marks significant changes in vegetational composition at this site. Aquatic pollen grains disappear from the diagram at this level, and important Equisetum, Ericoid, and finally Sphagnum phases follow, indicating very shallow water conditions (see chapter 5). In this essentially late hydroseral stage one would expect alternating waterlogging and drying of the surface, and thus conditions suitable for corrosion of included pollen grains. Yet, in contrast to Cambusbeg and Tynaspirit 1, the corroded pollen content is surprisingly low. In both Tynaspirit 1 and Cambusbeg there is a strong representation of corroded pollen in the Flandrian sediments though aquatic pollen grains are still recorded and the Equisetum and Sphagnum phases are not represented.

There is thus a problem in interpreting the pattern of deteriorated pollen curves at Amulree 1. With the large representation of broken pollen grains (30% to 50%) it would appear that some form of water transport of grains into the basin continued throughout basin deposition into zone Amlm. The low proportions of corroded grains, particularly in zones Amlk, Aml1 and Amlm, do not support a hypothesis of periodic oxidation of the peat deposits. However, there is a strong representation of amorphous grains and it may be that amorphous conditions can be induced by chemical rather than, or in addition to, physical modifications (see part 3, this chapter). There is also the possibility that many of the chemically-deteriorated grains in the upper zones at Amulree 1 can be attributed to long-distance transfer and the reflotation process.

D. MOLLANDS (Fig. 31).

(i) Description

Section A. (see part 2, this chapter).

Section B. Crumpled pollen grains play an insignificant role in this diagram, except in zones Mob and Moc. The dominant deterioration class at this site is the amorphous class, with especially strong representation in upper zone Moe and zone Mof. Amorphous pollen account for over 50% of the total in the upper part of zone Moe and the lower part of zone Mof. Frequencies for corroded grains fluctuate throughout, generally ranging between about 15% and 35%. Two marked expansions of the corroded pollen curve (to 65% and 48%) occur within zone Mog.

There are strong relationships between the composition of the deteriorated pollen and lithology at this site. Corroded and amorphous grains increase gradually and consistently throughout lithostratigraphic unit 3, a dry, compact peat. The change to lithostratigraphic unit 4, a Sphagnum peat with wood fragments, coincides with the domination of deteriorated pollen totals by amorphous grains. The marked expansions of corroded pollen occur within lithostratigraphic unit 5 (Sphagnum peat), and with a return to dry, compact peat (lithostratigraphic unit 6) corroded grains decrease markedly, to less than 5% of the total, and the amorphous and broken categories increase in relative importance.

Section C. The fluctuations in the curves of the more important contributors to the deteriorated pollen totals, of which nine are presented here, accord with major changes in the corresponding curves of the normal pollen diagram (Fig. 24). Thus, for instance, percentages of deteriorated *Corylus* pollen are high where *Corylus* is relatively important in Fig. 24. *Alnus* and *Pinus* are particularly striking in this relationship between curves in section C, Fig. 31, and the corresponding pollen curves in Fig. 24.

Section D. There is a very noticeable pattern in this section. The percentage of deteriorated *Betula* pollen is lowest (usually 10% or less) where *Betula* is dominant in the normal pollen diagram, *viz*. in zones Mob, Moc, Mod and Moh. There are very high totals of *Betula* recorded for this site. Where *Betula* decreases in importance the proportion of deteriorated *Betula* grains increases markedly to between 40% and 60%. Corroded and amorphous grains account for most of the deterioration, but there is also a strong representation of the broken category.

Section E. A similar relationship to that described in section D exists in the relationship of the *Corylus* deteriorated pollen curve to the *Corylus* curve in the normal pollen diagram. Where the relative percentages are high, as in zones Mod and Moh (Fig. 24) the deteriorated *Corylus* pollen percentages are low. Where *Corylus* declines in importance in zones Moe, Mof and Mog, there are markedly increased deteriorated *Corylus* frequencies. In zone Moe corroded and amorphous grains are important, in zone Mof amorphous grains are predominant, and in the upper part of Mof and in zone Mog broken grains also become important.

Section F. In zones Moe and Mof, where *Alnus* is a major taxon in the tree pollen assemblage, the deteriorated pollen of *Alnus* also record high percentages. However, in zone Moh, where *Alnus* continues to be the dominant tree taxon represented in the pollen diagram, deteriorated Alnus pollen percentages are markedly reduced (from more than 50% to less than 10%). The deterioration of Alnus is mainly corrosion, with amorphous grains second in importance.

Section G. The percentage of deteriorated Pinus grains is consistently at around 20% - 25% of total Pinus pollen at those levels where Pinus makes an important contribution to the pollen assemblages. The deterioration is almost exclusively in the broken category.

(ii) Interpretation

The marked increases in total deteriorated pollen grains (section A) within zones Moe, Mof and Mog, correspond with lithostratigraphic units 4 and 5. These units consist of a loose Sphagnum peat, with small wood fragments in lithostratigraphic unit 4. Although leaves and stems of Sphagnum were recorded in these lithostratigraphic units, the deposits are exceedingly poor in Sphagnum spores (Fig. 24). Corroded pollen frequencies are important in zones Moe, Mof and Mog, and in lithostratigraphic unit 6, where there is a change to a more compact, dark, fine-detritus peat, corroded grains decrease in importance and there is an increase in the number of Sphagnum spores recorded in Fig. 24. It would appear that Sphagnum spores are very susceptible to corrosion.

The hydroseral sequence at this site is described in detail in chapter 11. The drying-out of the bog surface, indicated by the Equisetum-Cyperaceae-Salix phases, would account for the increase in corroded pollen frequencies in zones Moe, Mof and Mog. If amorphous conditions can also be produced by chemical alterations, then this might account for some of the increases in amorphous pollen totals, especially in zone Mof. A simplified explanation of the relationship of the deteriorated pollen totals to the peat stratigraphy is tentatively advanced:

(a) In zones Mob, Moc and Mod, a basin lake existed. The percentage of deteriorated grains in these zones is generally very low, and most of the deteriorated grains probably derived from washing-in of soil particles from the basin catchment.

(b) In zones Moe, Mof and Mog the lake had dried due to a combination of falling water-table and the accumulation of basin peat deposits. The high percentages of corroded and amorphous grains probably derived from redeposition of grains from collapsed unconsolidated basin-edge deposits, and the oxidation of basin peat *in situ* due to periodic aeration. The increased proportions of corroded grains in zone Mog indicate increased oxidation.

(c) The darker, more compact fine-detritus peat in zone Moh, the preservation of *Sphagnum* spores, and the reduction in the proportion of corroded and amorphous grains, indicate a return to reducing conditions in the basin, possibly related to higher water-tables at this time.

The pollen curves in section C (Fig. 31) suggest contemporaneous deterioration. This is especially apparent in the relationship of the curves for *Alnus* and *Pinus* in section C to the *Alnus* and *Pinus* curves in Fig. 24. However, the curves in section C, Fig. 31, are misleading as the high percentages are a statistical consequence of the high influx of pollen of certain taxa, particularly of *Betula* and *Corylus*, at this time. From sections D and E (Fig. 31) it can be seen that the highest proportions of deteriorated *Betula* and *Corylus* grains occur in zones Moe, Mof and Mog, after the dominant phases of *Betula* and *Corylus* in Fig. 24. One explanation of this could be that oxidation affected zones Moe, Mof and Mog, resulting in the deterioration of about 30% of *Betula* and *Corylus* grains *in situ*. However, a problem encountered here is that several other taxa that are dominant in these zones are barely affected by oxidation processes. Thus, for instance, Filicales spores, *Polypodium* spores, *Salix* pollen, *Quercus* pollen, and Cyperaceae pollen are all important in this part of the diagram but record very low frequencies of deteriorated pollen grains and spores. It is realised that the problem of differential susceptibility to oxidation is important here, and it is likely that the scheme outlined above, where deterioration in zones Moe, Mof and Mog is mainly attributed to aeration, is too simplified.

The clear relationship of the total deteriorated pollen curve (section A, Fig. 31) to variations in peat stratigraphy and to the vegetational transition between aquatic and marsh-fen conditions (Fig. 24) suggest oxidation to be the likely cause of deterioration in zones Moe, Mof and Mog. However, a large number of the deteriorated grains of Betula, Corylus, Alnus and Pinus in these zones are only broken. This suggests that movement of soil and organic particles into the basin was still an active process at this time. Alternatively, redeposition of younger unconsolidated deposits from the edge of the basin, exposed as a result of lowered water-tables (and thus oxidised), could also be advanced as an explanation of the high percentages of deteriorated Betula and Corylus grains. This could easily be accounted for should deposits of zone Mod in age have collapsed into the middle of the basin during the accumulation of deposits of zones Moe, Mof and Mog in age.

An interesting pattern is revealed by the Alnus curve of section F (Fig. 31). There is a very marked decline in the percentage of deteriorated Alnus grains at the Mog/Moh zone boundary, yet Alnus continues to be the dominant arboreal taxon in the pollen assemblages (Fig. 24). The high frequencies of deteriorated Alnus grains in zone Mog cannot be primarily attributed to the redeposition of earlier deposits since Alnus is not a major taxon in the pollen diagram prior to zone Mog. The reflotation process could be suggested as an explanation of much of the corroded and amorphous pollen influx in zones Moe, Mof and Mog, but the marked reductions of deteriorated Alnus, Betula and Corylus grains, all coincident with the Mog/Moh pollen zone boundary, suggest a relationship to a change within the basin deposits. It seems probable, therefore, that most of the deterioration, at least in zone Mog, and possibly also in zones Moe and Mof, can be attributed to in situ chemical processes.

E. GLENTURRET (Fig. 32).

(i) Description

Section A. (see part 2, this chapter).

Section B. A very straightforward pattern is revealed in this section, with corroded and amorphous pollen increasing in importance from the base to the top of the sampled deposits, and broken pollen frequencies gradually declining throughout the diagram. Amorphous and broken pollen account for over 75% of total deteriorated grains except in zones Gld and Gle where corroded grains increase in importance. Crumpled pollen frequencies fluctuate without any apparent pattern (between values of 1% and 17%) throughout the diagram. There is no obvious relationship between variation in peat stratigraphy and changes in the composition of deteriorated pollen totals.

Section C. The curves in section C basically reflect the influx of the corresponding taxa as revealed by the relative frequency percentages in Fig. 26, with two notable exceptions. Firstly, there are no deteriorated *Salix* grains recorded in zone Glb, though *Salix* continues to be an important contributor to the pollen influx. Secondly, also in zone Glb, the deteriorated Cyperaceae curve does not reflect the marked increase of the Cyperaceae pollen influx in this zone.

Sections D - I. As with all the other sites previously described, the percentages for deteriorated *Betula* and *Corylus* grains increase after the dominant *Betula* and *Corylus* phase (Glb) in the normal pollen diagram (Fig. 26). With the exception of zone Gla, *Salix*, Gramineae and Cyperaceae record very low frequencies of deterioration throughout the diagram, whereas *Pinus* is consistently recorded at 20% - 40% in section E. The full information regarding the variation of the different classes of deterioration for each taxon is not available for this site.

(ii) Interpretation

The correspondence between the curves in section C and those in the main pollen diagram (Fig. 26) suggests, as in previous diagrams, that deterioration of pollen grains at this site is either due to penecontemporaneous redeposition or to post-depositional modification of the pollen exines *in situ*. There are two factors at Glenturret that contrast with the diagrams previously discussed. Firstly, broken pollen grains are dominant in the Glenturret diagram, and this is perhaps surprising in this small basin which has a limited catchment. Breakage of grains at this site, which in any case affects a small proportion of the pollen influx in zones Gla and Glb, could be related to physical deformation as a result of pressure induced by sediment load. Sheet or soil wash is not, however, entirely discounted. Secondly, as in the Mollands diagram, the *Sphagnum* peat of lithostratigraphic unit 4 is not reflected by the curve for *Sphagnum* spores in the pollen diagram. *Sphagnum* spores increase in representation in lithostratigraphic unit 5, a drier, more compact fine-detritus peat. In contrast to the Mollands diagram, however, corroded and amorphous grains actually increase in frequency in lithostratigraphic unit 5, thus the absence of *Sphagnum* spores in lithostratigraphic unit 4 cannot be entirely attributed to oxidation.

The very high percentages of *Salix*, Cyperaceae, Gramineae, and possibly also *Ulmus* pollen in zones Glc, Gld, and Gle, where a very small proportion of the pollen influx of each of these taxa is deteriorated, suggest that they were taxa that grew extremely close to the basin, with the result that pollen grains were deposited directly into the basin without undergoing redeposition or exposure to reflotation processes.

6. DISCUSSION

Within the Lateglacial sediments at Cambusbeg, Tynaspirit, and Amulree there are a number of consistent features in the frequency diagrams for deteriorated pollen. All three diagrams reveal very high percentages of deteriorated pollen grains within the Lateglacial assemblage zones, particularly within minerogenic deposits (Fig. 33), and the deterioration is predominantly physical deterioration (breakage and crumpling). All three sites experienced a marked increase in the proportion of corroded pollen grains in the Loch Lomond Stadial assemblage zones (Fig. 34). This has been interpreted as indicating the redeposition of pollen grains from soils that had developed on surrounding slopes during the milder Lateglacial Interstadial phase. At Cambusbeg and Tynaspirit there are notable decreases in the deteriorated pollen curves (Figs. 18 and 15) immediately below the lower boundary of the Loch Lomond Stadial pollen zone (Fig. 33). This is interpreted as indicating the development of a stable soil, with a close vegetation cover preventing the washing-out of soil particles and of pollen grains. This feature is less well marked at Amulree and could indicate that the development of a closed vegetation cover and soil development were retarded or locally more incomplete here during the Lateglacial Interstadial.

Crumpled pollen grains increase in proportion with depth of sediment in each of the deteriorated pollen diagrams with the exception of Glenturret. It is difficult to interpret this information in isolation since the frequencies of crumpled pollen grains are relatively dependent on the absence of all other signs of deterioration. Nevertheless, this relationship could suggest that crumpling is related to compaction within the sediments and is not directly related to other environmental factors. The degree of compaction that can develop within basin sediments is well illustrated at Bigholm Burn, Dumfriesshire (Moar, 1969a), where basal organic deposits have been severely contorted by overlying sediments. Compaction may also be an important contributing factor in the production of broken grains and amorphous conditions in pollen exines.

The best known indicator of chemical alteration of pollen exines is corrosion, but this is extremely variable in its representation at each of the five sites. For instance, at Cambusbeg (Fig. 29) it is the

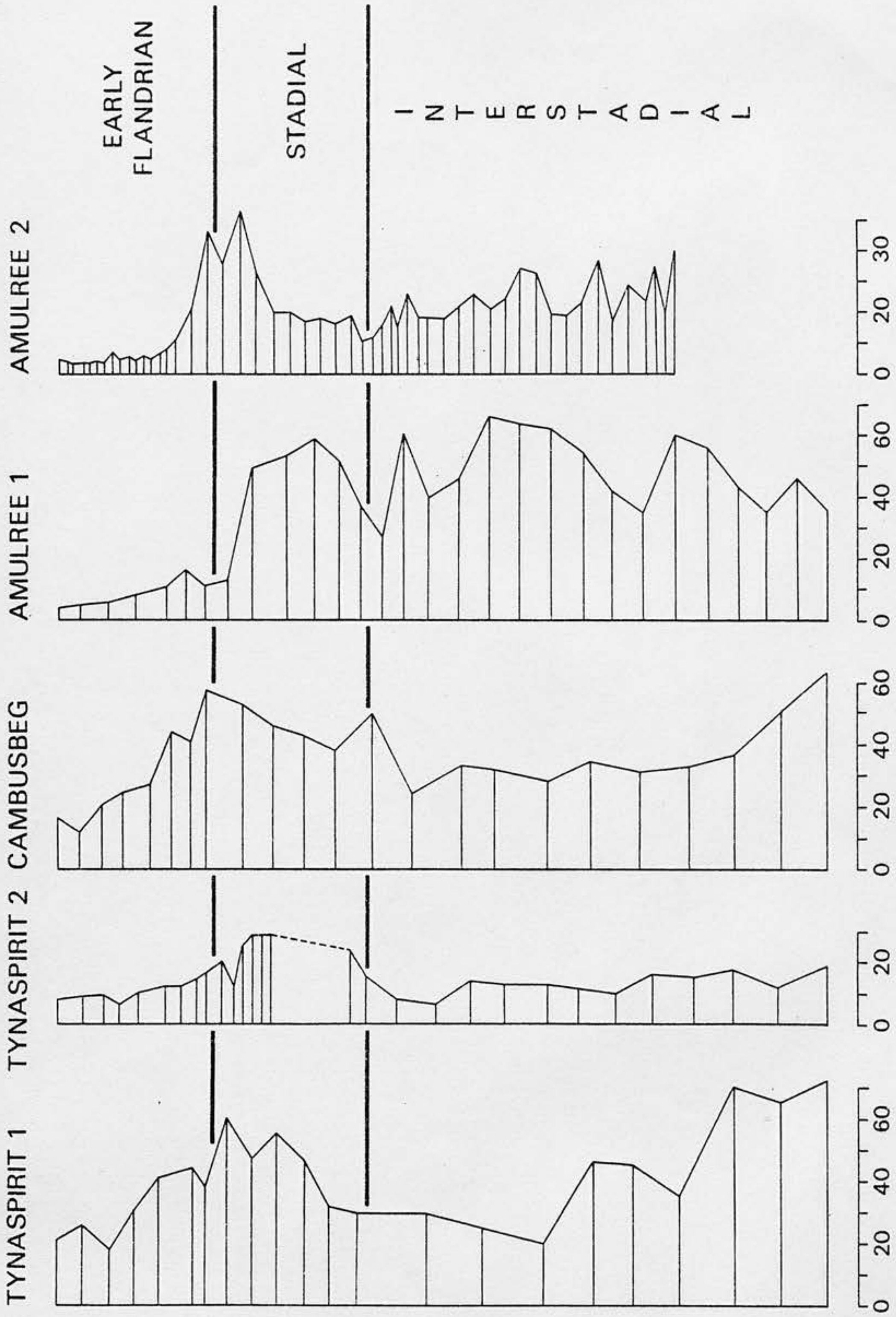


FIGURE 33 Deteriorated pollen grains as percentages of total land pollen in Lateglacial and early Flandrian sediments at Tynaspirit, Cambusbeg and Amulree (scale represents percentages).

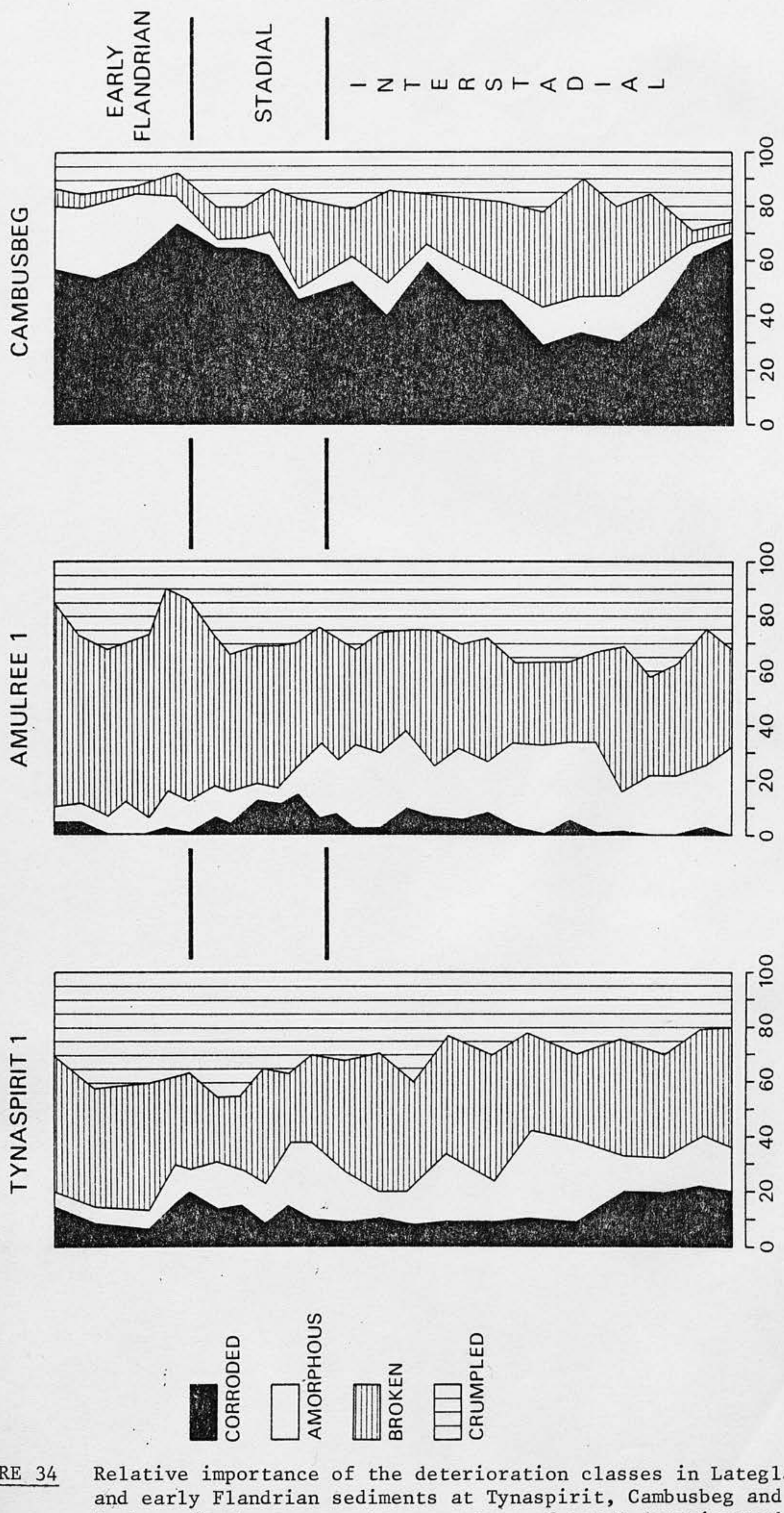


FIGURE 34 Relative importance of the deterioration classes in Lateglacial and early Flandrian sediments at Tynaspirit, Cambusbeg and Amulree (scale represents percentage of total deteriorated pollen grains at each site).

dominant deterioration class throughout the diagram, with the exception of zones Cla and Clc. In the Flandrian zones there is little relationship between lithology and the importance of corrosion in the deteriorated pollen frequencies. At Amulree, on the other hand (Fig. 30), corroded grains are only significant in the pollen assemblage zones that follow the dominant hazel phase (Amlg and Amlh) in the diagram, viz. in zones Amli and Amlj. The pattern at Amulree is similar to that at Mollands (Fig. 31) where an increase in deteriorated pollen totals and in the proportion of corroded grains occur at a lithological transition from dry compact peat to loose Sphagnum peat. At both sites this feature also coincides with major changes in local vegetation composition, from communities indicative of shallow-water conditions, to sedge-fen and Sphagnum-bog communities (see chapter 5).

It is noticeable at Amulree, Mollands and Glenturret, that the dramatic Corylus reduction that marks the end of the dominant hazel phase at each site (zones Amlg and Amlh, Fig. 21; zones Moe-Mof, Fig. 24; zone Glb, Fig. 26) coincides with major changes in peat stratigraphy and with other major vegetational changes. This is also accompanied by marked increases in the percentages of deteriorated pollen grains at each site. At Tynaspirit and Cambusbeg there are also marked increases in percentages of deteriorated pollen grains, especially in corroded grains, at the termination of the dominant hazel phase (zone Tlh, Fig. 16; zone Cli, Fig. 19) but there are no changes in peat stratigraphy, and no indications of the late hydroseral stages recorded at the other three sites. A continued significant representation of aquatic grains, such as Potamogeton, Myriophyllum and Sparganium, at Cambusbeg and Tynaspirit indicates continuous waterlogging of these two basins.

A common factor in all five deteriorated pollen diagrams, therefore, is the occurrence of markedly increased deteriorated pollen totals, usually including significant increases in corroded grains, at what is usually referred to as the Late Boreal Period. Evidence from the British Isles in general has established that during the Boreal the generally warmer and drier climate favoured the development of deciduous closed forest ecosystems in which shrub species, such as Corylus, became part of a subordinate stratum. This would therefore explain the dramatic decline in the representation of hazel in pollen diagrams from most parts of the British Isles. It has also been established that during the Late Boreal Period, and also during the later Sub-Boreal Period, water levels in a number of basins were lowered, and this led to a break in sedimentation and/or the re-working of older sediments (Pennington, 1947; Walker and Godwin, 1954; Walker, 1955; Godwin, 1956, 1975). Thus the evidence points to rather dry conditions in the Late Boreal Period. In addition to the evidence of lowered lake levels, there is evidence from several parts of highland Britain for drying out of mire surfaces at this time (Pennington, 1969).

High percentages of corroded pollen grains have previously been reported from deposits of Boreal age (Godwin, 1943; Newey, 1966), and this suggests that deteriorated pollen grains are characteristic of Boreal deposits in general. A possible explanation of the corroded grains recorded is that they are related to increased activity of soil organisms. Beneath the mixed deciduous forest canopy of Boreal times, at a time of relatively dry and warm climatic conditions, there probably developed a type of brown-forest soil profile (see chapter 12) with a characteristic mull leaf-litter. Mull conditions support large populations of bacteria, soil fungi, and soil macro- and microfauna which result in a relatively rapid modification of raw organic detritus to form soil humus. It is likely that any pollen grains incorporated into the organic soil horizons are also decomposed by this activity (Dimbleby, 1961), and some of the pollen of Boreal soils may have entered stream or lake waters as a result of erosion or collapse of stream banks or of bioturbation.

On evidence of chemical changes in lake sediments Mackereth (1966) and Pennington (1965) suggest that the Late Boreal Period was also associated with significant leaching of soils, resulting in increased solute transport to lake basins. Their hypothesis is that the dry conditions led to lowered water-tables which in turn resulted in increased percolation of ground and surface water through soils. Since a mature soil with a high humus content had developed during the Boreal, the humus would have added to the acidity of the dilute carbonic acid that is commonly a characteristic of rain-water, and this would have led to the increased leaching of soluble bases. This hypothesis is supported by Vasari and Vasari's studies (1968) of microfossil and macrofossil floral remains, especially of aquatic flora, in loch sediments from northern Scotland. They suggest that in the early part of the Boreal soils were little leached and a birch-hazel vegetation developed rapidly. The changing aquatic communities of the lochs show that the supply of the bases to the loch waters gradually increased throughout the Boreal, and towards the end of the Boreal evidence for increased acidity in the lochs suggests that progressive leaching of soils continued in the surrounding catchments. "This must have been a common course of developments in much of Northern Scotland. The information obtainable from pollen finds of aquatic species from Zone VI unanimously suggests the prevalence of poor conditions towards the end of this period" (Vasari and Vasari, 1968, p.86).

On the other hand, it is normally assumed that a warm and dry climate significantly reduces leaching (Tansley, 1949). Instead there tends to be an upward movement of soil water by capillary action, resulting in an accumulation of bases in upper soil horizons thus neutralising acids caused by the decomposition of organic matter. Nutrient recycling is also an important factor in closed deciduous forest ecosystems. Thus the position of the water-table is only one variable that affects the process of leaching, and it may be a minor one, for more important are the character of the litter deposited by the vegetation and the ratio of evaporation and transpiration to precipitation.

There thus seems to be some conflict in concepts concerning the Boreal

Period. On the one hand there is evidence for mature forest vegetation cover and favourable climatic conditions, when, one could assume, leaching would be at a minimum. On the other hand there is firm evidence for increased leaching having taken place. Nevertheless, the bulk of the evidence indicates that major environmental changes took place during the Late Boreal Period. Some of these major changes, and their possible implications for the analysis of the deteriorated pollen content of basin sediments, can be itemised as follows:

1. Lake levels were lowered, and this resulted in exposure of and re-working of deposits from the edge of the basins. This therefore probably accounts for much of the corroded pollen recorded after the period of hazel dominance.
2. Mire surfaces and soil surfaces were dried, and this may have led to the deterioration of peat or soil surfaces, particularly in exposed or marginal situations. This may therefore have resulted in the release of pollen grains into streams in the catchments surrounding the basins.
3. Lowered water-tables also resulted in increased percolation, and this may have led to washing-in of pollen into the basins, especially at Tynaspirit, Cambusbeg, and Mollands where the basins are formed in sand and gravel deposits.
4. Bioturbation of deposits within the basins would have increased as a result of the more favourable climatic conditions at this time, and this may account for some of the physically deteriorated grains, as well as the inclusion of corroded grains where aerated soil deposits near the basin were disturbed.

A combination of all of these factors probably explains the marked increases in deteriorated pollen totals at all five sites, and may explain variation in deteriorated pollen content between the five sites. The recurrent coincidence of the <u>Corylus</u> decline and the increase in content of deteriorated pollen grains at all five sites (pollen zone boundary Tlg/Tlh, Fig. 16; Clh/Cli, Fig. 19; Mod/Moe, Fig. 24; Amlh/Amli, Fig. 21; Gla/Glb, Fig. 26) suggests that both are related to major regional environmental changes, and it is concluded that these features in the pollen diagrams are roughly synchronous, and record the much drier conditions of the Late Boreal Period.

Another common feature in each of the five deteriorated pollen diagrams is the increase in the representations of deteriorated Betula and Corylus pollen grains following the dominant phases of these taxa in the normal pollen diagrams. This is such a well-marked feature in each diagram, and occurs regardless of variation in lithology, in pollen assemblage composition, and of sediment depth (cf. 7.0 m below surface at Amulree, 4.0 m at Tynaspirit, 9.0 m at Cambusbeg, and 4.0 m at Mollands), that it must be at least partly explained by a regional factor as well as by local factors at each individual site. This is interpreted as indicating the redeposition of younger exposed deposits at the edge of the basins as a result of lowered water-tables. The deposits exposed would probably have been those of the Betula- and Corylus-dominated assemblage zones, and redeposition of these grains (and others) may have occurred following a period of oxidation.

There is evidence from two of the sites, viz. Mollands and Glenturret, of a later phase of re-expansion of Betula and Corylus, coincident with a dominant Alnus phase and increased percentages of Gramineae and Cyperaceae. At both sites this coincides with marked reductions in frequencies of total deteriorated pollen grains. This is interpreted as indicating a return to higher water-tables, probably related to wetter climatic conditions, and this would have resulted in a cessation or slowing down of the processes of redeposition of pollen grains in the basins and in surrounding catchments. In both basins there is a change in peat stratigraphy from Sphagnum peat to the accumulation of more compact, darker peat. There is not enough evidence to decide whether the sharp decline in deteriorated pollen totals is a consequence of changes within the basins only, or whether it is also related to regional environmental changes affecting surrounding slopes. The latter seems likely, since there is widespread evidence for an oceanic climate in Britain following the relatively dry Late Boreal

Period. However, in interpreting the deteriorated pollen totals there is the additional problem that some of the deterioration could be caused by reflotation processes, and it is impossible on available data to separate out this category throughout the profiles.

Most of the deterioration of *Pinus* pollen is probably caused by transportation in streams. *Pinus* was never a dominant local vegetation component at any of the sites, and almost exclusively the deteriorated *Pinus* grains are broken. *Pinus* pollen could suffer damage in streams by physical abrasion, as a result of attack by bacteria, or after having been ingested as part of the food supply of stream fauna.

The deteriorated *Alnus* pollen curves are perhaps best explained through the reflotation hypothesis. High percentages of deteriorated *Alnus* grains are recorded at Cambusbeg and Mollands. In zone Clh (Figs. 19 and 29), if this deterioration is due mainly to oxidation of *in situ* *Alnus* pollen, then it is difficult to explain why the dominant *Betula* and *Corylus* pollen are not also heavily affected. Evidence from all the sites suggests *Betula* and *Corylus* to be two of the most susceptible pollen types to processes of deterioration. In zone Mog (Figs. 24 and 31), if a lowered water-table and consequent oxidation and re-cycling of sediments is invoked as the sole explanation of the source of deteriorated *Alnus* pollen at this level, then one would have expected other taxa with seemingly much higher values of pollen influx to have been similarly affected. One explanation of the deteriorated *Alnus* pollen curve could be that zones Clh and Mog record the spreading of *Alnus* into the Teith Valley region, but that the taxon was not yet locally important at these sites. With the establishment of *Alnus* locally (and the expansion of *Alnus* may have been accelerated by a change to wetter conditions at the Mog/Moh boundary, as suggested above) the local production of *Alnus* pollen grains would ensure direct sedimentation into the basins, reducing the effects of reflotation.

The most difficult category of deteriorated grains to analyse is that of the amorphous class. Cushing (1964, 1967) and Birks (1970) attribute degraded (amorphous) grains to the effects of physical alteration of pollen grains, but there are indications from the five deteriorated pollen diagrams presented here to suggest that amorphous grains result from chemical alteration processes as well. Thus the amorphous class of deteriorated grains often increases in percentage where the corroded class becomes more significant, and amorphous grains often increase in proportion towards the surface of basin sediments, as at Glenturret (Fig. 32). In addition, the highest percentages of amorphous pollen grains are usually recorded at those levels suspected to have experienced oxidation due to exposure as a result of lowered water tables (zones Moe and Mof, Fig. 31; zone Glc, Fig. 32).

7. CONCLUSIONS

It is quite clear that though there are a number of consistent features within the five frequency diagrams for deteriorated pollen records, it is extremely difficult to establish the relative importance of the various possible causes of deterioration. Within the Lateglacial zones physical deterioration is dominant, and the highest deteriorated pollen totals are recorded here (Figs. 33 and 34). In general chemical alteration becomes increasingly important in shallower sediments. In situ chemical alteration does not appear to account for the total chemical deterioration in late hydroseral peat accumulations, and it is possible that some degree of soil wash or redeposition has occurred throughout almost all of the sediments examined. The clearest and most easily compared phase in the Flandrian deposits in each site is that related to the drier conditions and lowered water tables of the Late Boreal Period, when deteriorated pollen totals markedly increase in each profile.

An important feature of the frequency diagrams for deteriorated pollen is that the total amount of deterioration, and also to some degree the type of deterioration, give some indications of the possible degree of distortion of the regional and local pollen assemblage zones, despite the inability to determine the precise causes of deterioration. It is thus important to present an analysis of these data prior to an attempt to correlate the various pollen diagrams and to establish regional pollen assemblage zones. Both the evidence from the normal pollen diagrams (chapters 4 and 5) and from the frequency diagrams for deteriorated pollen (this chapter) are used in chapter 7 to compare local vegetational developments.

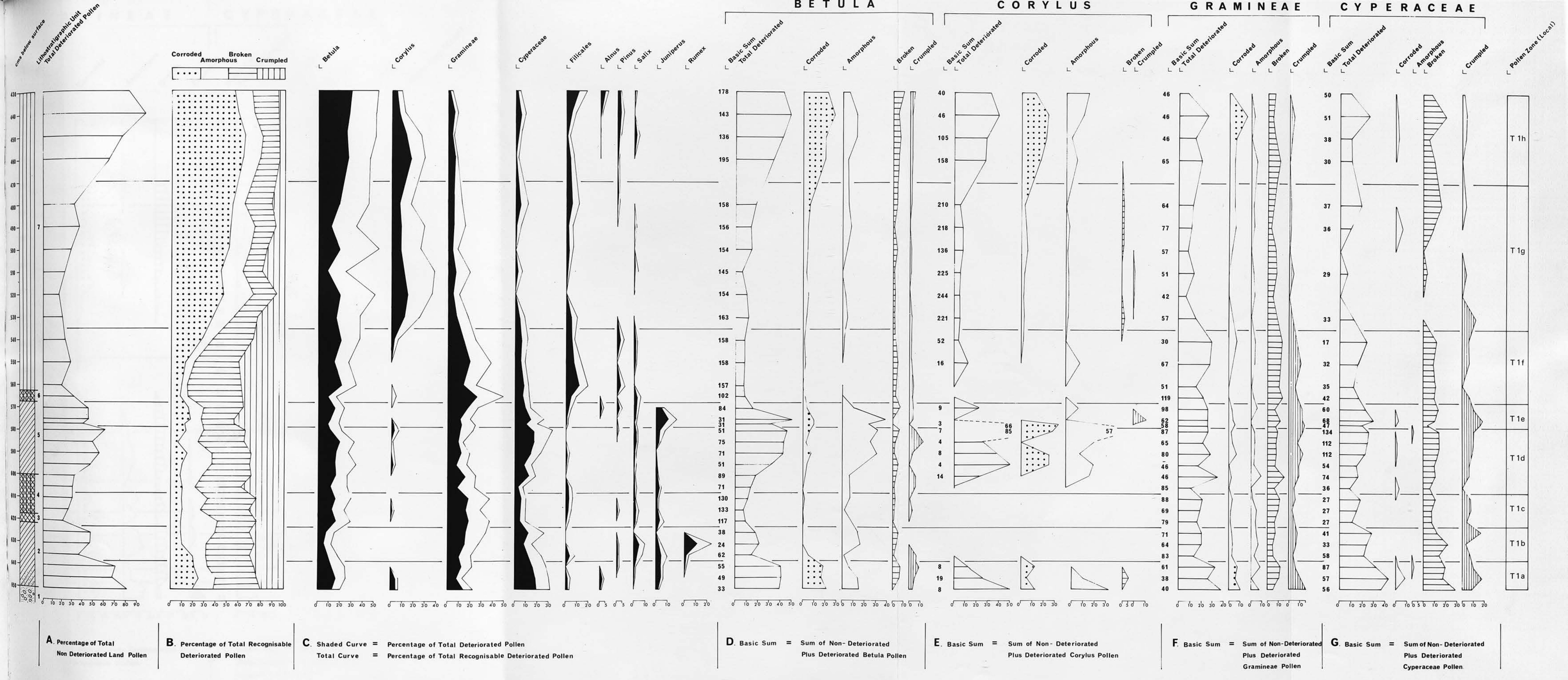


FIGURE 28 TYNASPIRIT 1: deteriorated pollen grains and spores in Lateglacial and early Flandrian sediments.

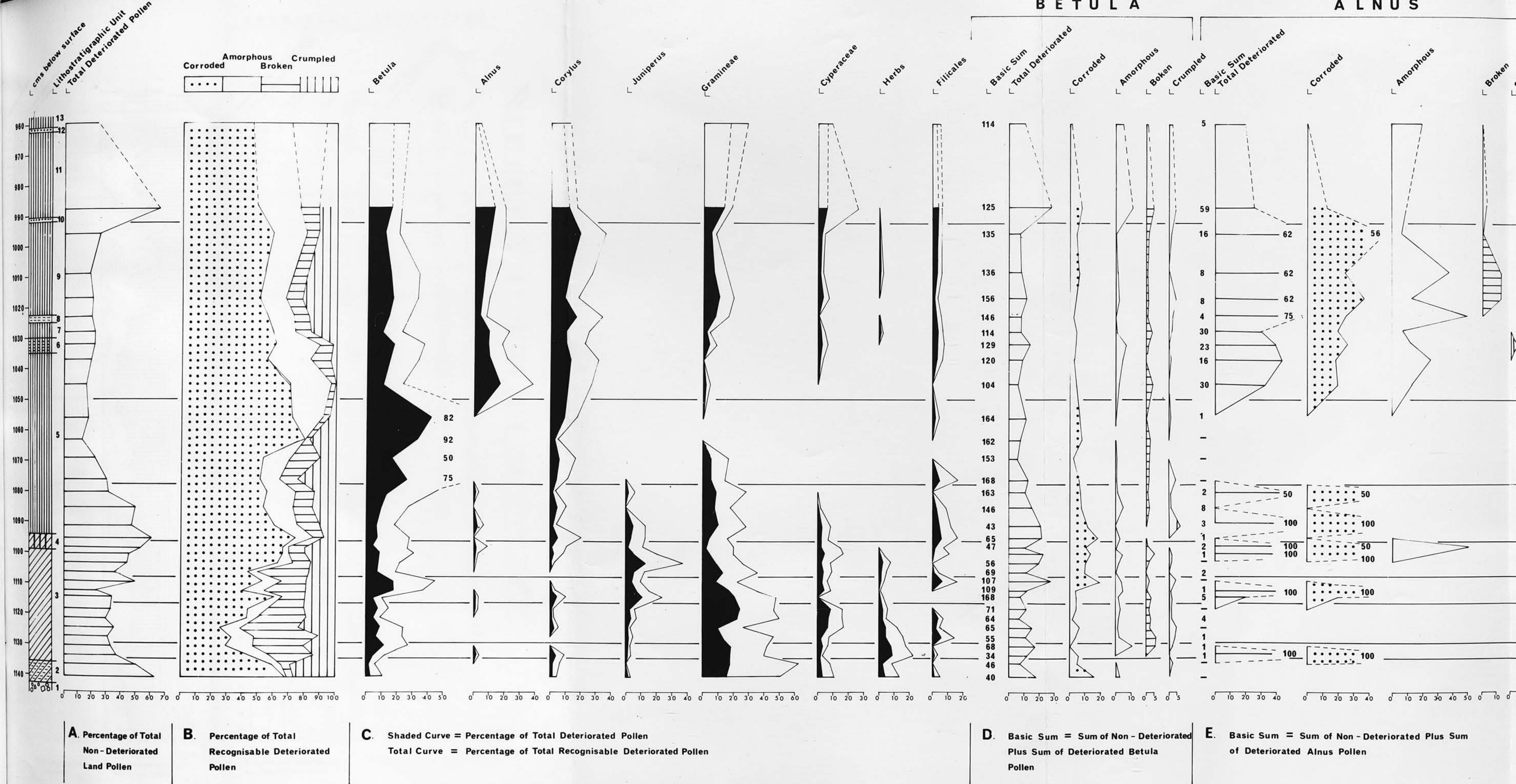
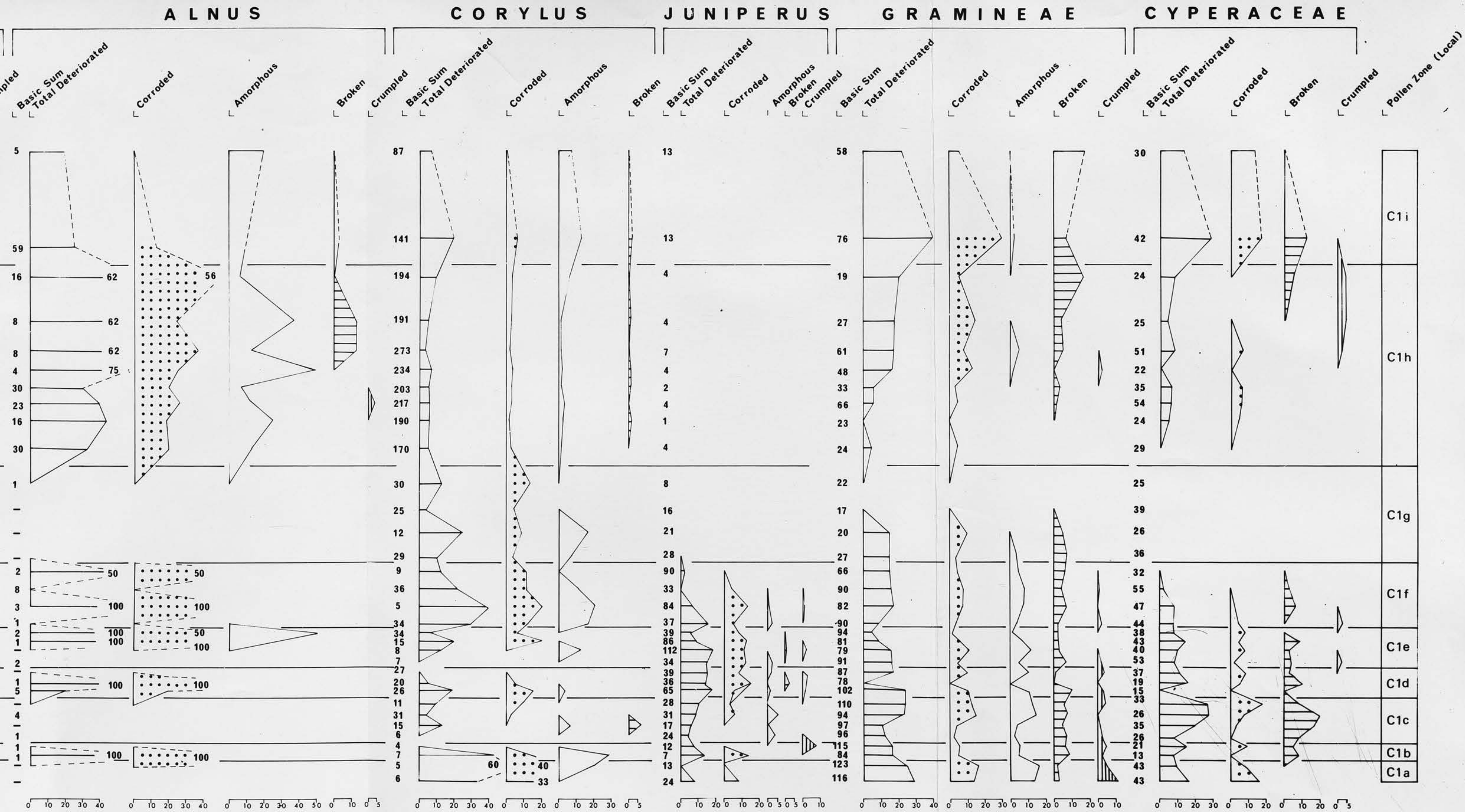


FIGURE 29 CAMBUSBEG: deteriorated pollen grains and spores in Lateglacial and early Flandrian sediments. 'Herbs' excludes Gramineae and Cyperaceae.



E. Basic Sum = Sum of Non - Deteriorated Plus Sum of Deteriorated Alnus Pollen

F. Basic Sum = Sum of Non - Deteriorated Plus Deteriorated Corylus Pollen

G. Basic Sum = Sum of Non-Deteriorated Plus Deteriorated Juniperus Pollen

H. Basic Sum = Sum of Non - Deteriorated Plus Deteriorated Gramineae Pollen

I. Basic Sum = Sum of Non-Deteriorated Plus Deteriorated Cyperaceae Pollen

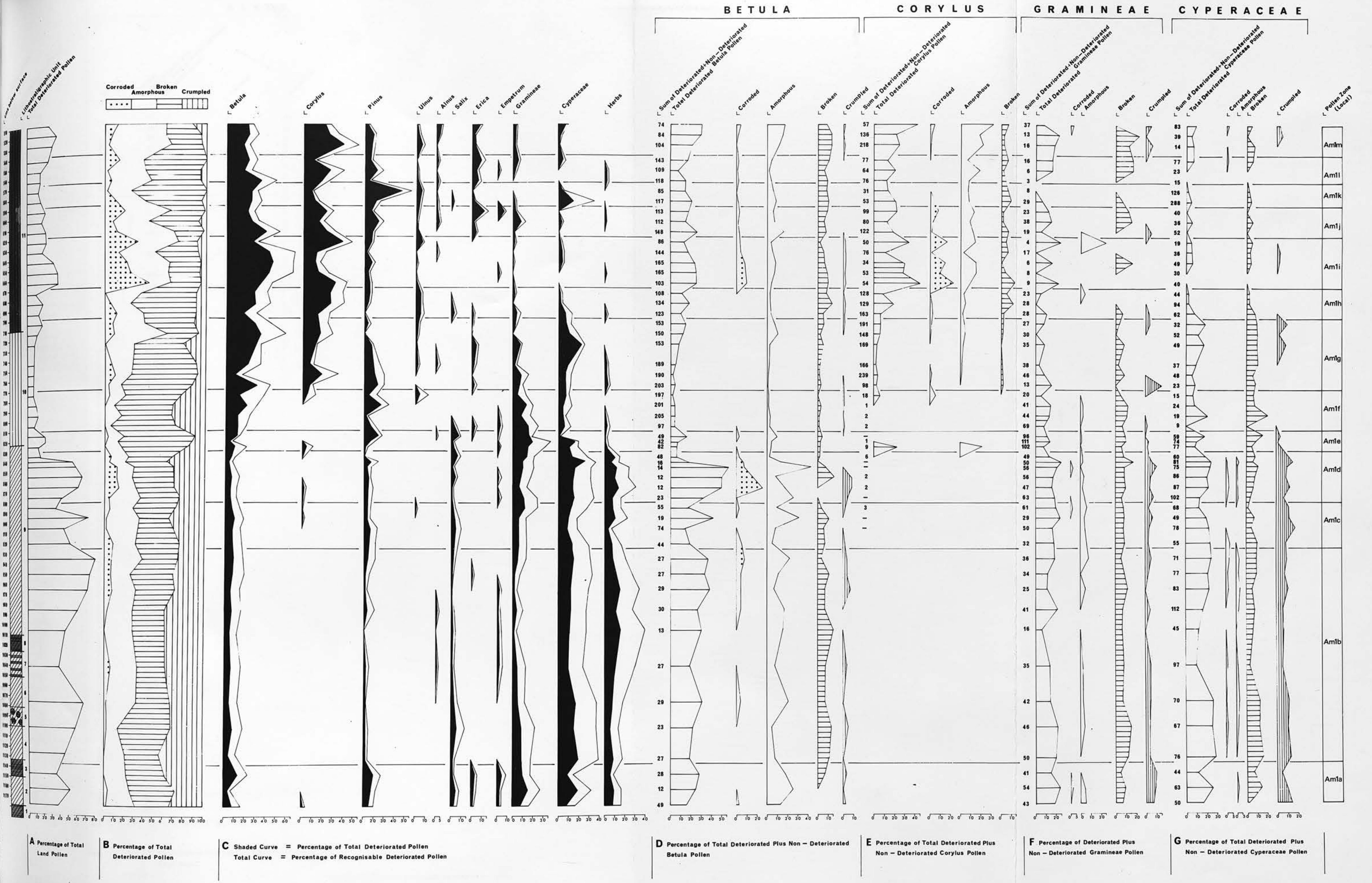


FIGURE 30 AMULREE 1: deteriorated pollen grains in Lateglacial and early Flandrian sediments. 'Herbs' excludes Gramineae and Cyperaceae.

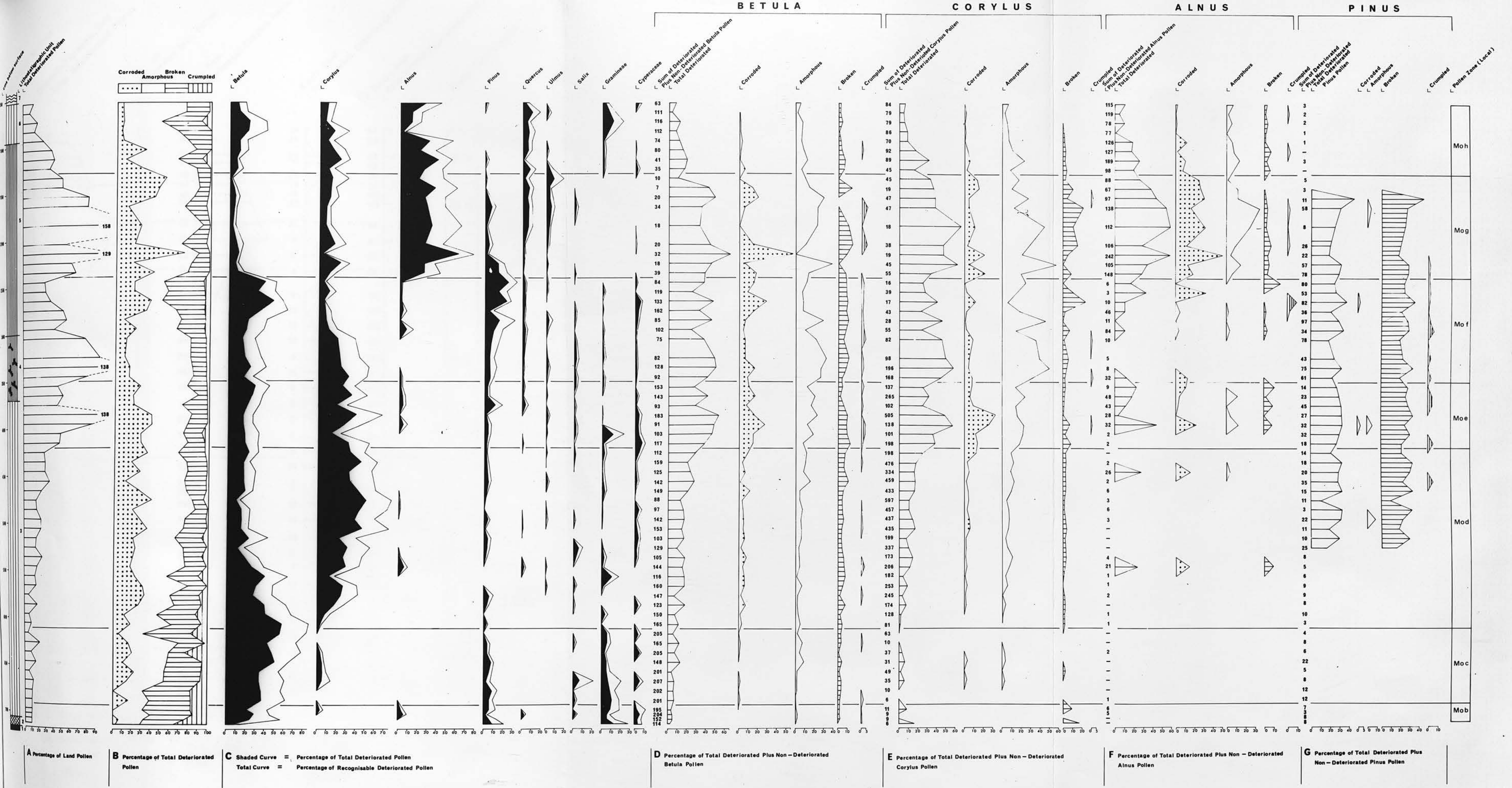


FIGURE 31 MOLLANDS: deteriorated pollen grains in Flandrian sediments.

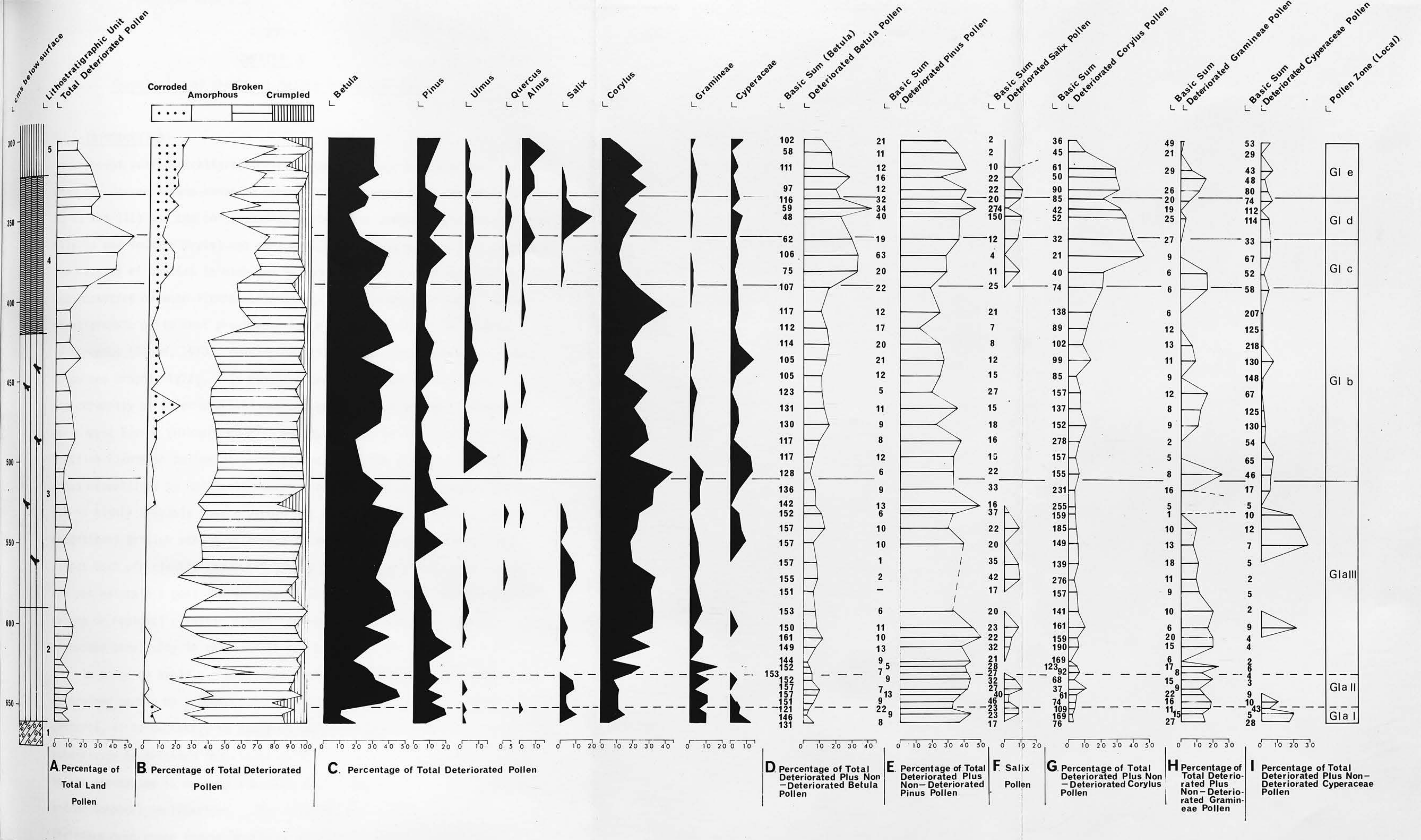


FIGURE 32 GLENTURRET: deteriorated pollen grains recorded for basal sediments.

CHAPTER 7

Correlation of the Local Pollen Assemblage Zones

1. INTRODUCTION

Recent pollen-stratigraphic investigations from Scotland have shown that the Jessen-Godwin zonation scheme for the Lateglacial period (zones I, II and III) and the corresponding chronostratigraphic terms (Older Dryas, Allerød and Younger Dryas) can no longer be strictly applied (see chapter 9). The results of studies in highland Britain as a whole have revealed marked discrepancies between lithostratigraphic, biostratigraphic and climatostratigraphic units that previously had been considered to be broadly synchronous (Coope, 1970; Pennington, 1970; Pennington and Bonny, 1970; Coope and Brophy, 1972). In addition there is evidence for marked asynchroneity of major vegetational changes in the Flandrian throughout north-west Europe (Hibbert et al., 1971), and the validity of dividing Scottish Flandrian pollen diagrams according to the scheme of pollen zones established by Godwin is now regarded by some as very questionable. "It is highly probable that a single set of pollen zones, such as the traditional British scheme of zone I to zone VIII (Godwin, 1940, 1956), cannot both efficiently and meaningfully subdivide all the pollen sequences and yet maintain a position in time established by either radiocarbon dating or regional climatic events" (Birks, 1973, p.281). This is discussed more fully in chapters 11 and 12.

In order to avoid the arbitrary subdivision of pollen diagrams determined partly by preconceptions of climatic, ecological, or temporal criteria, it is necessary to adopt an inductive approach to biostratigraphic subdivision by defining individual pollen assemblage zones for each site, before attempting to draw up a broader scheme that has climatic, ecological, and/or temporal implications. The diagrams presented in this thesis have therefore been zoned independently on the basis of local pollen (and certain spore) assemblages alone (see chapter 3), the subdivisions of each profile having been defined by stable or constant relative values of different pollen or spore types, irrespective of their climatic or ecological affinities. The local pollen assemblage zones as defined here are thus biostratigraphic units that, initially, carry no climatic, ecological or temporal implications.

However, in comparing the local pollen assemblage zones defined for each site it is assumed that major climatic changes, where these can be inferred from the diagrams, are more or less synchronous for southern Perthshire. It is likely, for instance, that the onset and the termination of the Loch Lomond Stadial are synchronous within such a limited area, and that the diagrams can be correlated on the basis of these boundaries. For various reasons, discussed in chapter 5, Tynaspirit 2 is designated the type-site for the Lateglacial vegetational succession, and Mollands is the type-site for developments in the Loch Lomond Stadial/Flandrian transition period, and they form the bases for comparisons between the various diagrams. The comparison of major Flandrian vegetational changes are, however, more problematic, and no single site is employed as a type-site for Flandrian developments.

Table 4 shows the correlation of the local pollen assemblage zones (with the exception of the upper Flandrian zones, especially at Mollands, Glenturret, and Amulree 1) from the five sites discussed in this thesis. The criteria employed in establishing this correlation table are discussed briefly in this chapter, for much of the critical material has been discussed in detail in chapters 4, 5 and 6. The table itself establishes the basis for comparisons of vegetational developments throughout southern Perthshire during the Lateglacial and parts of the Flandrian periods. All the radiocarbon dates that have been obtained for these sites are also shown in Table 4. These are not, however, accepted as chronostratigraphic

TABLE 4 Correlation of the local pollen assemblage zones

TIME-PERIOD	TYPICAL VEGETATION COVER	LOCAL POLLEN ASSEMBLAGE ZONES: TYNASPIRIT		CAMBUSBEG	AMULREE		MOLLANDS	GLENTURRET
FLANDRIAN	Variable forest Communities		Tlh	Cli	Amli		Moe	Glb
FLANDRIAN	*Betula-Corylus*		Tlg	Clh	Amlh Amlg		Mod	Gla – – ? – –
FLANDRIAN	*Betula*	9,260±100 T2g	Tlf	Clg	Amlf	9,115±120	9,365±120 Moc	
FLANDRIAN	*Betula-Juniperus*	T2f	Tle	Clf	Amlf	Am2g	Mob (III-IV) 10,480±155	
FLANDRIAN	*Juniperus*	10,420±160	Tle	Clf	Amlf	10,270±100	Mob (I-II) 10,670± 85	
FLANDRIAN	*Salix-Empetrum*	T2e	Tle	Clf	Amle	Am2f 10,770± 90	Moa	
LOCH LOMOND STADIAL	Herbaceous and moss communities	T2d	Tld	Cle	Amld	Am2e Am2d		
LATEGLACIAL INTERSTADIAL	*Betula-Juniperus* or dwarf-shrub communities	11,385±290 T2c	Tlc	Cld	Amlc	Am2c Am2b		
LATEGLACIAL INTERSTADIAL	Herbaceous and dwarf-shrub communities	12,395±195 T2b 12,750±120 T2a	Tlb ? Tla	Clc Clb Cla	Amlb Amla	Am2a		

upper limit to sampled sediments

TABLE 4 Correlation of the local pollen assemblage zones

TIME-PERIOD	TYPICAL VEGETATION COVER	LOCAL POLLEN ASSEMBLAGE ZONES: TYNASPIRIT	TYNASPIRIT	CAMBUSBEG	AMULREE	AMULREE	MOLLANDS	GLENTURRET
F L A N D R I A N	Variable forest Communities		T1h	C1i	Am1i		Moe	G1b
	Betula-Corylus		T1g	C1h	Am1h Am1g		Mod	G1a
	Betula	9,260±100 T2g	T1f	C1g		9,115±120	9,365±120 Moc	?
	Betula-Juniperus	T2f			Am1f	Am2g	Mob (III-IV) 10,480±155	
	Juniperus	10,420±160	T1e	C1f		10,270±100	Mob (I-II) 10,670± 85	
	Salix-Empetrum	T2e			Am1e	Am2f 10,770± 90	Moa	
LOCH LOMOND STADIAL	Herbaceous and moss communities	T2d	T1d	C1e	Am1d	Am2e Am2d		
LATEGLACIAL INTERSTADIAL	*Betula-Juniperus* or dwarf-shrub communities	11,385±290 T2c	T1c	C1d	Am1c	Am2c Am2b		
	Herbaceous and dwarf-shrub communities	12,395±195 T2b 12,750±120 T2a	T1b ? T1a	C1c C1b C1a	Am1b Am1a	Am2a		

upper limit to sampled sediments

definitions for the various biostratigraphical horizons. Their validity and significance are discussed in detail in chapter 10.

2. LATEGLACIAL POLLEN ASSEMBLAGE ZONES: TYPE-SITE TYNASPIRIT 2

The lowest zone at Tynaspirit 2 (Fig. 17), zone T2a, is characterised by high percentages of Rumex and Empetrum, with Gramineae, Cyperaceae and Salix also important. This is succeeded by a Gramineae-Cyperaceae-Filipendula zone where aquatic pollen and Betula and Juniperus pollen all increase in importance (zone T2b). Zone T2c is a Betula-Juniperus zone where these two taxa dominate the pollen spectra. Although this part of the profile (lithostratigraphic units 3, 4 and 5) is subdivided into three biostratigraphic units, these three units are interpreted as indicating a gradually developing vegetation, from an open vegetation cover in zone T2a (indicated by the percentages of Rumex, Thalictrum and Compositae) to a more closed and mature vegetation cover in zone T2c, supporting shrubs of juniper and birch, and probably also trees of birch. No major climatic changes can be inferred from the biostratigraphic criteria within zones T2a, T2b and T2c.

At the zone boundary T2c/T2d a number of marked changes occur within the pollen curves. Betula and Juniperus pollen frequencies decline and these are replaced in the spectra by increased percentages of Rumex, Gramineae and Cyperaceae. Also of great significance in zone T2d are the relatively high percentages of Artemisia, Selaginella and Lycopodium, and the marked increase in the proportion of deteriorated pollen grains recorded, all of these features indicating soil disturbance and a very open vegetation cover around the Tynaspirit basin at this time. Zone T2d clearly indicates a period of marked vegetational revertence, and is equated with the Loch Lomond Stadial. This period of vegetational revertence is terminated by major vegetational changes at the T2d/T2e pollen zone boundary, with the reduction and virtual disappearance of those taxa indicating disturbed soil conditions, accompanied by a reduction in the proportion of deteriorated pollen grains, and with marked expansions in grass and aquatic pollen percentages. Pollen zones T2e and T2f indicate the development of a more stable soil with a vegetation cover locally dominated by birch and juniper.

A radiocarbon date of 12,750 ± 120 B.P. was obtained from the sediments at the T2a/T2b pollen zone boundary. This date, if acceptable, is minimal for the deglaciation of the basin, and hence the Callander area. In addition, up to 10 cm of minerogenic lacustrine sediment (lithostratigraphic unit 2) occurs below this horizon. The date supports a number of other dates from Scotland that indicate deglaciation of much of Scotland, including Highland areas, from the Late Devensian ice sheet shortly after 13,000 B.P. (see chapter 9). However, the date of the T2c/T2d pollen zone boundary, 11,385 ± 290 B.P., and that of the T2e/T2f boundary, 10,420 ± 160 B.P., are in conflict with the conventional dates for the beginning and end of the Loch Lomond Stadial in Scotland (chapters 9 and 10). Thus the chronostratigraphic criteria from Tynaspirit 2 are regarded as somewhat questionable, and since this site is advanced as the model on which to base the comparison of Lateglacial pollen assemblage zones for sites in this part of the Grampian Mountains, only a very simplified model can at present be outlined. A two-part Lateglacial vegetational sequence is recognised, and a third phase indicates the beginning of the Flandrian period:-

(a) a long period of apparently uninterrupted plant colonisation from sparse pioneer vegetation to a closed grassland with a locally dense shrub vegetation dominated by juniper and willow, and with scattered copses of tree birch between the time of deglaciation from the Late Devensian ice sheet at Callander (possibly before 12,750 B.P.) and the onset of the Loch Lomond Stadial;

(b) a period of vegetational revertence, including evidence for very disturbed soils and open vegetation, with the highest recorded percentages in the diagram of <u>Artemisia</u>, <u>Selaginella</u>, and <u>Lycopodium</u>;

(c) a re-expansion of shrubs and grasses, indicating a return to a closed grassland and cessation of soil disturbance by solifluction or cryoturbation around the basin, and at the same time the sudden development of a rich aquatic flora within the basin.

Phase (a) is termed the Lateglacial Interstadial. There is no evidence to support a major subdivision of the Lateglacial Interstadial phase into, for example, the Jessen-Godwin zones I and II. In addition there is no indication of a climatic fluctuation during the early part of the Lateglacial Interstadial that could be equated with the Bölling Oscillation of continental north-west Europe. Evidence for an equivalent to this oscillation has been found in certain sites in northern Britain (Bartley, 1962; Pennington, 1970, 1975; Pennington and Sackin, 1975). Phase (b) is equated with the Loch Lomond Stadial. Only one phase of vegetational revertence is recognised in the Tynaspirit 2 diagram. The earliest Flandrian pollen spectra (phase (c)) form a very pronounced part of the diagram due to the scale of the changes in the pollen curves. This phase, the Loch Lomond Stadial/Flandrian transition, is analysed in more detail in section 4 below.

3. CORRELATION OF LATEGLACIAL POLLEN ASSEMBLAGE ZONES FROM TYNASPIRIT, CAMBUSBEG AND AMULREE

Since it has been shown that the samples on which the Tynaspirit 1 pollen diagram (Fig. 15) is based were subject to contamination during sampling procedures (see chapters 4 and 5) care has to be taken when comparing the Lateglacial pollen assemblage zones of Tynaspirit 1 with those of Tynaspirit 2. It has already been established that a Lateglacial vegetation sequence can be recognised at Tynaspirit 1, and though there is an overall basic similarity between Figs. 15 and 17, there are some notable differences.

A phase of marked vegetational revertence occurs in zone T1d which equates with zone T2d described above. However, since the pollen content of the clays of lithostratigraphic unit 5 at Tynaspirit 1 is extremely low, the effects of biostratigraphic contamination and the resulting distortion of the pollen curves are probably greatest in this part of the diagram, and thus one cannot rely on the relative percentage values. Nevertheless, Selaginella is clearly represented most significantly and consistently in zone T1d, and the spectra in general, as well as the markedly increased percentages of deteriorated pollen grains, suggest comparisons with zone T2d.

At both Tynaspirit 1 and Tynaspirit 2 the interpretation of the Loch Lomond Stadial/Flandrian transition is complicated, but there are remarkable similarities in both diagrams. Thus in the upper part of the minerogenic sediments of lithostratigraphic unit 7 (Fig. 17) a marked peak in Juniperus pollen frequencies occurs which coincides with high percentages of Artemisia, Rumex, and deteriorated pollen grains. This is followed by a Gramineae-Cyperaceae-Empetrum phase, which coincides with a major expansion of aquatic flora in the basin. Similarly at Tynaspirit 1 (Fig. 15) a marked juniper peak occurs in the upper part of lithostratigraphic unit 5, and this also coincides with high values of Artemisia and deteriorated pollen grains. This phase is also in turn succeeded by a Gramineae-Cyperaceae phase accompanied by a major expansion in aquatic flora.

The marked Juniperus peaks within the Loch Lomond Stadial minerogenic sediments of both profiles (from separate but closely located basins within the Tynaspirit glacial deposits) probably indicate some degree of time-lag between biostratigraphic and lithostratigraphic records of environmental change. In both basins the change from minerogenic to organic sedimentation, roughly coincident with pollen zone boundaries T2d/T2e and T1e/T1f, reflects the development of a closed vegetation cover on relatively undisturbed soils on surrounding slopes. The major increases in the percentages of juniper pollen grains that occur below this boundary suggest that juniper may have been able to survive the stadial conditions at Tynaspirit, perhaps in a prostrate form, and may have flowered profusely immediately after climatic conditions had improved at the end of the Loch Lomond Stadial. On the other hand, the development of a closed vegetation cover and the cessation of minerogenic inwash may have been somewhat delayed. Any increase in the influx of juniper pollen grains would have been exaggerated as a result of the low pollen influx from the mainly herbaceous flora around the basin at that time.

It would appear, therefore, that pollen zone boundary T1e/T1f can be correlated with pollen zone boundary T2d/T2e, and that the biostratigraphic boundary for the close of the Loch Lomond Stadial (phase (b), above) is represented by pollen zone boundary T1d/T1e. The transition between non-polleniferous sediments and polleniferous sediments within zone T2d at Tynaspirit 2 is the probable equivalent of this zone boundary, but since there are no pollen spectra available for the lower part of lithostratigraphic unit 7 (Fig. 17) this boundary is not marked on this diagram.

As at Tynaspirit 2 the Lateglacial Interstadial phase is represented by three pollen zones at Tynaspirit 1. However, these are not thought to be directly comparable. The Betula-Juniperus phase at Tynaspirit 2 (zone T2c) is not recognised in the Tynaspirit 1 diagram since percentages of juniper pollen grains do not emphatically increase in the Lateglacial Interstadial sediments. It is thought that this cannot be explained as a result of the effects of contamination since the chamber would have penetrated deposits of extremely poor pollen content (lithostratigraphic unit 5) before coming into contact with the Lateglacial Interstadial organic sediments that are relatively rich in pollen grains (lithostratigraphic unit 4). The juniper percentages are also so high in zone T2c that the differences between zone T2c and zone T1c cannot be explained by distortion of the biostratigraphic records within zone T1c. Thus the contrast in percentages of juniper between zones T1c and T2c are thought to reflect real differences in the relative importance of juniper in the immediate locality of these two basins at this time. This perhaps emphasises the point that pollen zone boundaries T2b/T2c and T1b/T1c are biostratigraphic zone boundaries only, and they need not necessarily be strictly synchronous owing to the possibility of local discrepancies in vegetational developments (and hence in local pollen production). However, it seems likely that the marked increase in percentages of Betula pollen grains that occurs in the upper part of the Lateglacial Interstadial deposits in both basins is synchronous as these two basins are only about 100 m apart, and thus the T2b/T2c boundary is correlated with the T1b/T1c boundary in Table 4.

Pollen zone T1a indicates a phase not recognised in the Tynaspirit 2 pollen diagram. This is an early Lateglacial Interstadial zone dominated by Cyperaceae and high percentages of deteriorated pollen grains, and also including increased Corylus and Betula percentages which are interpreted as indicating the effects of contamination in sediments with an extremely low pollen content (see chapter 5). Thus zone T1b is interpreted as encompassing both zones T2a and T2b, and pollen zone T1a records an earlier or a much more open vegetation phase than is recorded in the lowest sediments at Tynaspirit 2.

Similar arguments to those developed above can be used to relate the Cambusbeg Lateglacial pollen assemblage zones (Fig. 18) to the Tynaspirit 2 diagram. However, Fig. 18 is very badly affected by contamination and biostratigraphic distortion (see chapters 4 and 5) and so only a few of the most essential features are referred to here. Zone C1e records a phase of marked vegetational revertence, recognised through increased percentages of Selaginella, deteriorated pollen grains, and slightly increased percentages of Artemisia (probably depressed by the effects of contamination). Zone boundary C1e/C1f is equated with zone boundaries T1e/T1f and T2d/T2e, and the high juniper percentages in zone C1e may have a similar explanation as those of zones T2d and T1e discussed above. The C1a/C1b boundary may equate with the T1a/T1b boundary since the pollen spectra of zones T1a and C1a are in some respects similar, especially with respect to the very high percentages of deteriorated pollen grains recorded in these zones.

The pollen profiles from the basal sediments of Amulree are markedly different from those from the basal sediments at Cambusbeg and Tynaspirit. Amulree 2 (Fig. 22) is discussed first since this pollen diagram, based on samples collected by enlarged piston corer, is regarded as a more accurate record of vegetational history than that of Amulree 1. At Amulree 2 the lowermost sampled sediments contain spectra dominated by spores of Lycopodium and Selaginella, with pollen grains of Caryophyllaceae and Artemisia also important. This indicates an open vegetation and disturbed skeletal soils during zone Am2a. Throughout zones Am2a, Am2b and Am2c Lycopodium and Selaginella percentages consistently decline, giving way to a Rumex-Gramineae-Cyperaceae phase. In zone Am2c increased percentages of Juniperus and Empetrum indicate that vegetational succession was in progress, culminating in the Lateglacial Interstadial at Amulree with the immigration of shrub elements, which in turn suggests a tendency to the development of more stable soils. The deteriorated pollen percentages also consistently decline throughout zones Am2a, Am2b, and Am2c. The vegetation was never, however, completely closed, as there are consistent significant representations of Lycopodium, Selaginella, Rumex and Artemisia throughout this time period.

A number of important changes take place at the Am2c/Am2d boundary. Lycopodium and Selaginella percentages increase, and Juniperus, Rumex, Cyperaceae and Gramineae totals decline. In zone Am2e percentages for Empetrum also decline, while Artemisia, Caryophyllaceae and other herbaceous pollen curves increase. In addition there is a marked increase in percentages of deteriorated pollen grains in zone Am2e. Thus zones Am2d and Am2e represent a period of vegetational revertence, where the trends established in zones Am2a, Am2b and Am2c are reversed. Since no periods of vegetational revertence have been recognised in early Flandrian pollen diagrams from the British Isles, and since only one period of vegetational revertence is recognised at the Lateglacial type-site, Tynaspirit 2, the revertence phase at Amulree is equated with zone T2d and hence with the Loch Lomond Stadial. The consistently high percentages of herbaceous pollen grains and of spores in the Lateglacial Interstadial zones at Amulree have important ecological implications, as does the lithostratigraphic sequence at this site. These are discussed in chapter 8. A Betula- dominated or Betula-Juniperus Lateglacial Interstadial phase is not represented at Amulree 2, and the increased Betula and Pinus percentages of zones Am2d and Am2e probably indicate the effects of long-distance transfer of pollen grains, affecting especially those sediments where pollen content would be expected to be at a minimum.

The Loch Lomond Stadial/Flandrian transition is marked initially by increases in pollen percentages of Gramineae, Cyperaceae and Rumex at the Am2e/Am2f boundary, but more definite evidence of an end to poor climatic conditions and disturbed soil conditions occurs at the end of zone Am2f, where there occur marked increases in percentages of pollen grains of juniper and birch. Pollen zone boundary Am2e/Am2f is correlated with zone boundary T1d/T1e, and zone boundary Am2f/Am2g with pollen zone boundaries T2d/T2e, T1e/T1f, and C1e/C1f (Table 4).

The Amulree 1 pollen diagram is badly affected by contamination and it is much more difficult to interpret percentage variations in this diagram (Fig. 20). In general the deteriorated pollen percentages are higher in this diagram than in Amulree 2. However, there are basic similarities between pollen diagrams Amulree 1 and Amulree 2 in the variations of the Lycopodium, Selaginella, Rumex and Cyperaceae frequency curves. The high proportion of deteriorated pollen grains, the high herbaceous pollen content, and especially the highest percentages in the diagram of Artemisia pollen grains, all indicate pollen zone Am1d to represent the Loch Lomond Stadial (phase b) in this diagram. Thus pollen zone boundary Am1c/Am1d is correlated with Am2c/Am2d, and Am1d/Am1e with Am2e/Am2f.

The percentages for Betula and Juniperus in zone Am1c are shown by the Amulree 2 diagram to be highly misleading, since the latter pollen diagram reveals that a Betula-dominated phase did not occur at Amulree, and Juniperus percentages were always below about 16% in Lateglacial Interstadial sediments. Further, it is not possible to relate pollen zones Am1a, Am1b and Am1c, and pollen zones Am2a, Am2b and Am2c to the Lateglacial Interstadial zones at the other sites. The number of subdivisions of the Lateglacial Interstadial vegetation sequence depends on a number of complex local site factors, such as the time of initial sedimentation in the basin, the rate of sedimentation, and the nature and rate of vegetational succession. The sequence may correspond approximately with the Jessen-Godwin zones I and II (as indicated on Figs. 15 and 17), but the age of the lowest pollen assemblage zone at each site is unknown, and is likely to be variable from site to site.

It is concluded that the boundaries for the upper Lateglacial Interstadial zones in Table 4, recording the climax at each site of the vegetational response to Interstadial climatic improvement, and the pollen zone boundaries that are equated with the Loch Lomond Stadial, can be correlated with some confidence. However, correlation of the local pollen assemblage zones established for the lowest minerogenic sediments at each of the above three sites (four separate basins) is highly questionable. Since the chronostratigraphic data available for early Lateglacial Interstadial deposits relates only to Tynaspirit 2, and since there are reservations concerning the radiocarbon dates from this site, the correlation of these pollen zone boundaries remains problematic.

4. LOCAL POLLEN ASSEMBLAGE ZONES FROM THE LOCH LOMOND STADIAL/ FLANDRIAN TRANSITION - CORRELATION WITH THE TYPE-SITE, MOLLANDS

The most detailed records for the Loch Lomond Stadial/Flandrian transition are provided in Fig. 25. In most of the pollen diagrams presented in this thesis this transition period is represented by a dominant

Juniperus phase, or by a Betula-Juniperus phase, though in some a preceding dwarf-shrub phase can also be recognised (see chapter 4). At Mollands the dwarf-shrub phase and the juniper heath phase can be divided into a number of sub-zones that are impossible to delimit in other pollen diagrams. These are described in detail in section 6, chapter 4, but can be summarised as follows:

Zonation of Mollands profile, zones a - d:

4.	Zone Mod		Betula-Corylus
3.	Zone Moc		Betula-dominated
2.	Zone Mob	sub-zone IV	Betula-Juniperus-Filipendula
		sub-zone III	Juniperus-Betula
		sub-zone II	Juniperus
		sub-zone I	Empetrum-Juniperus
1.	Zone Moa	sub-zone III	Empetrum-dominated
		sub-zone II	Salix-Empetrum-Rumex
		sub-zone I	predominantly herbaceous phase

The variation in sediments (chapters 2 and 4), variation in pollen content, and the detailed pollen assemblage records all suggest a gradually developing vegetation cover with stabilisation of soils on catchment slopes following deglaciation of the Mollands site. There is no vegetational revertence phase recorded in the comparatively deep sediments at Mollands. Instead there is a succession of vegetation stages from a herbaceous phase to a dwarf-shrub phase, then to a juniper heath, and then, following the immigration of birch trees in zone Moc, to a hazel-birch vegetation cover in zone Mod.

The Juniperus-dominated phase (zone Mob, sub-zone II) has been radiocarbon-dated to 10,670 ± 85 B.P., and the Juniperus-Betula phase (zone Mob, sub-zone III) to 10,480 ± 150 B.P. Both of these dates are older than the conventional dates for the close of the Loch Lomond Stadial (see chapter 8). It is not immediately apparent why these dates, and those from Tynaspirit 2 discussed earlier, are considerably older than expected, but it is significant that these dates were obtained from gyttja material, and serious doubts are now being expressed about the reliability of gyttja as a medium for radiocarbon dating (R.E.G. Williams, personal communication). In view of the reservations concerning the Lateglacial and Loch Lomond Stadial/Flandrian transition dates, the date for the immigration of Corylus at Mollands, 9,365 ± 120 B.P., is also regarded as suspect.

The comparison of the Loch Lomond Stadial/Flandrian transition zones from the other sites with the detailed records from Mollands is complicated by a number of factors. Firstly, the rate of sedimentation during this period was in general far lower at the other sites than at Mollands, and thus biostratigraphic records for this period are condensed. Secondly, the sampling interval in most cases has been much wider than that employed in Fig. 25, and this too will tend to generalise biostratigraphical records. Thirdly, any distortion of the sediments, such as that resulting from bioturbation or, in the cases of Tynaspirit 1, Amulree 1, and Cambusbeg, from the use of the Hiller peat sampler, will result in further depression of the amplitude of individual pollen curves. Fourthly, the rate and type of vegetational succession can be very different between any two sites. To take one example, it has already been suggested (section 3, this chapter) that juniper may have survived the harsh climatic conditions of the Loch Lomond Stadial at Tynaspirit, and it may be that soils were only partially disturbed in the Teith Valley during this period. Thus the immigration of juniper, or at least the increase in the juniper pollen influx, may have been much more immediate around Tynaspirit following the Loch Lomond Stadial than at Mollands where, since the site was under glacier ice during the Loch Lomond Readvance (Thompson, 1972), a generally raw substrate would have retarded the immigration of juniper heath and of birch trees into the immediate vicinity.

In some of the pollen diagrams the early Flandrian dwarf-shrub phase is not represented. For example, in Tynaspirit 1 (Figs. 15 and 16) a zone dominated by juniper pollen grains immediately follows the Loch Lomond

Stadial pollen assemblage zone, and this in turn gives way to a Betula-dominated pollen assemblage zone. By comparison, however, in Tynaspirit 2 (Fig. 17), an Empetrum-dominated phase (zone T2e) is recorded during the Loch Lomond Stadial/Flandrian transition, and this is equated with zone Moa at Mollands. Thus zone T2f is equated with zone Mob.

The marked juniper rise in zone C1e at Cambusbeg (Fig. 18) has already been discussed (section 3, above). The increased percentages of Empetrum and Salix pollen grains in zone C1f suggest that the pollen curve fluctuations representing the early Flandrian dwarf-shrub phase at this site have been depressed as a result of one or more of the reasons stated above.

A Salix-Empetrum phase is recorded at Amulree 1 and Amulree 2, in zones Am1e and Am2f. These are therefore equated with zone Moa at Mollands, and the juniper-dominated zones Am1f and Am2g are equated with zone Mob. The beginning of juniper expansion has been dated to 10,670 ± 85 B.P. at Amulree 2, and a Betula-Juniperus phase has been dated to 10,480 ± 150 B.P. Neither the dwarf-shrub nor the juniper heath phase is represented in the Glenturret pollen diagram (Fig. 26).

The suggested correlation for the Loch Lomond Stadial/Flandrian transition local pollen assemblage zones is shown in Table 4. It is unlikely that these transitional pollen zones are exactly synchronous between each of the four sites, but it is difficult to test this conclusion since the few radiocarbon dates that are available are not accepted as chronostratigraphic definitions for developments in this period. It is possible, for instance, that there may be some time-lag between the Salix-Empetrum pollen assemblage zone at Amulree (zones Am1e and Am2f) and the corresponding zone in the sites in the Teith Valley. This argument is amplified by the variable records in the diagrams of the transition between juniper heath and a birch-hazel vegetation, discussed below.

5. CORRELATION OF FLANDRIAN LOCAL POLLEN ASSEMBLAGE ZONES

In each of the pollen profiles based on sediments from basins in the Teith Valley the following vegetational sequence is characteristic of the early Flandrian deposits:

(i) A widespread development of juniper-heath vegetation follows the close of the Loch Lomond Stadial, though in some of the diagrams this is first preceded by a dominant dwarf-shrub vegetation cover. This phase (phase c) has been described in detail in section 4.

(ii) There then follows a phase of birch immigration and, following a transitional phase of mixed juniper and birch, a vegetation cover strongly dominated by birch trees became established in the Teith Valley.

(iii) Hazel immigrated next, and the extremely high percentages of hazel recorded at Tynaspirit 1, Cambusbeg and Mollands indicate that Corylus was a firmly established shrub understorey in birch woodland in the Teith Valley, and there may also have been large stands of dominant hazel shrub.

This three-part sequence is clearly shown at each of the three sites in the Teith Valley. There is such a high degree of similarity between these diagrams that the correlation of the local pollen assemblage zones for the early Flandrian is fairly straightforward (Tables 4 and 5).

In the Amulree 1 pollen diagram (Fig. 21) a slightly different pattern emerges. Following a birch-juniper phase (zone Amlf) hazel immigrated immediately, so that the birch-juniper assemblage zone was succeeded directly by a birch-hazel phase (zone Amlg). It is suspected that, due to the higher and more exposed situation of the Amulree site, birch immigration was delayed, and that the birch forest was much more open than in the Teith Valley, with the result that juniper continued to be an important element of the vegetation cover until later in the Flandrian, and when hazel spread throughout southern Perthshire it was able to take advantage of the lighter forest cover of the area around Amulree. This probably explains why the predominantly birch phase that is recorded in the pollen diagrams from the Teith Valley is not represented in the Amulree pollen diagram.

It is thus evident that even in such a limited area as that of southern Perthshire some marked contrasts in vegetational composition have occurred, and that there may have been some significant time differences in the immigration of certain elements of the flora, such as birch and hazel, between upland and lowland sites. Three radiocarbon dates are available for the first significant representations of hazel in the pollen diagrams. A date of 9,260 ± 100 B.P. has been obtained for this event at Tynaspirit 2, the corresponding event has been dated to 9,365 ± 120 B.P. at Mollands, and from Amulree 2 a date of 9,115 ± 120 B.P. has been obtained. Taking some biostratigraphic criteria into consideration (see chapter 9), these dates would seem to indicate that hazel immigration was more or less synchronous at the three sites but, although they have been based on black organic muds and not on gyttja material, they must be regarded as questionable in view of the discrepancies in the lower dates from these sites.

In those pollen diagrams that record Flandrian events later than the immigration of hazel there is an association of two features that is common to each diagram: where Corylus begins to decline from its dominant position in the pollen diagram (usually a marked decline from percentages in excess of 100% of the arboreal pollen sum to percentages of about 30% - 60%) there is a marked increase in the proportion of deteriorated pollen grains recorded. It has been argued in chapter 6 that because these two features, and their coincidence in the diagrams, are so well marked in each diagram (with the exception of Glenturret - Figs. 26 and 32 - where, although the individual features are well marked, they do not coincide as closely as in other sites), and because they coincide irrespective of variation in such local factors as basin depth and sediment type, that they are both related to a widespread regional change in environmental conditions. It is therefore suggested that the following pollen assemblage zone boundaries are more or less synchronous: Tlg/Tlh (Fig.16), Clh/Cli (Fig. 19), Mod/Moe (Fig. 24), Amlh/Amli (Fig. 21), and Gla/Glb (Fig. 26).

Correlation of Flandrian local pollen assemblage zones following this event is much more complicated. There are strong contrasts in arboreal pollen percentage variations, even between the two neighbouring sites of Mollands and Cambusbeg. These two sites are only 1 km apart and yet a clear *Pinus* phase at Mollands (zone Mof) is not recorded in the Cambusbeg diagram. Similarly, *Ulmus* is much more strongly represented at Mollands than at Cambusbeg. However, a marked *Alnus* rise occurs in both diagrams and, again common to both diagrams, this is associated with a rise in *Quercus* pollen percentages and a marked decline in *Betula* pollen percentages. It is possible, therefore, that pollen zone boundaries Mof/Mog (Fig. 24) and Cli/Clj (Fig. 19) can be correlated.

Any correlation between local pollen assemblage zones for the later parts of the Flandrian is extremely conjectural. The Glenturret diagram resembles that of Mollands in some respects, but differs markedly in the overall pattern of the arboreal pollen curves. For example *Ulmus* is more strongly represented at Glenturret, and the relationship of the *Alnus* rise to the other arboreal pollen curves is quite different. The problems of correlation are compounded in the Amulree 1 diagram (Fig. 21) by the fact that *Pinus*, *Alnus* and *Ulmus* all record much lower percentages than at the other sites. It is difficult, therefore, to recognise common elements that can be designated as marker horizons in the pollen profiles.

Thus correlation of the later Flandrian local pollen assemblage zones is not given in Table 4, except for the suggested correlation of zone boundaries Mof/Mog and Cli/Clj. The composition of the local vegetation appears to have become increasingly more variable with time, and the interpretation of the vegetation cover in the Flandrian, and its environmental implications, are discussed in detail in chapter 11.

6. CONCLUSIONS

Though the correlation of the local pollen assemblage zones is by no means straightforward, there are a number of clear marker horizons that are common to several, if not all, of the diagrams. Thus the biostratigraphical boundaries for the Loch Lomond Stadial, the early Flandrian vegetation immigration sequence, and the Late Boreal change to dry climatic conditions (which can be recognised at each of the five sites by a marked increase in the proportion of deteriorated pollen grains) are easily recognised and provide a firm basis for correlation between the various diagrams. It is recognised, however, that these boundaries may not be exactly synchronous at each site. Correlation of other biostratigraphical boundaries, summarised in Table 4, is more tentative.

Correlation is easiest for the three sites in the Teith Valley, because of their close proximity to each other. Table 5 summarises the information from the pollen diagrams of Tynaspirit 1, Tynaspirit 2, Cambusbeg and Mollands, and indicates the probable relationship of the information from these sites with conventional terminology and chronology. The vegetational sequences from Amulree and Glenturret vary in detail from the generalised scheme presented in Table 5. In particular, important differences occur in the Lateglacial zones at Amulree, and in the upper Flandrian deposits that were sampled at Glenturret, Mollands, and Amulree 1. More detailed comparisons of the vegetation histories at each site are included in following chapters.

TABLE 5 A comparison of nomenclature and stratigraphic subdivisions employed in this thesis with conventional nomenclature and stratigraphic subdivision (radiocarbon dates in years B.P.)

Jessen-Godwin zones	Conventional terminology and radiocarbon dates	Terminology and division employed in this thesis	Generalised vegetation history for Teith Valley	Radiocarbon dates from the Teith Valley
ZONES IV - VIII	POSTGLACIAL	FLANDRIAN	Variable vegetation cover, with local dominance of different forest taxa	
			Betula–Corylus - Mixed Forest	
			Betula–Corylus	9,260
		10,000	*Betula*	9,365
			Betula–Juniperus	10,480
		LOCH LOMOND STADIAL	*Juniperus*	10,420 10,670
	10,300		*Empetrum–Salix*	
ZONE III	YOUNGER DRYAS		Herbaceous and moss vegetation, of especial significance are *Artemisia*, Caryophyllaceae, Cyperaceae, *Lycopodium* and *Selaginella*	
ZONE II	10,800 ALLERÖD 12,000	11,000	*Betula–Juniperus*	11,385 12,395
ZONE I	a) OLDER DRYAS b) BÖLLING ? c) OLDEST DRYAS?	LATEGLACIAL INTERSTADIAL 13,000	Period of plant colonisation and development of closed vegetation cover; mainly grassland and dwarf shrub communities	- - -? 12,750

CHAPTER 8

Vegetation history and palaeoenvironments during the Lateglacial and the Lateglacial/Flandrian transition in southern Perthshire

1. INTRODUCTION

A continuous record of ecological succession throughout the Lateglacial period is reflected in five pollen profiles presented in this thesis, viz. Tynaspirit 1 (Fig. 15), Tynaspirit 2 (Fig. 17), Cambusbeg (Fig. 18), Amulree 1 (Fig. 20), and Amulree 2 (Fig. 22). In each of these profiles the Lateglacial is divided on the basis of biostratigraphic criteria (see chapter 7) into a Lateglacial Interstadial and the Loch Lomond Stadial. It has been advanced that correlation between pollen sites within the limited region of southern Perthshire can be made on the basis of biostratigraphic horizons, such as that defining the transition between the Lateglacial Interstadial and the Loch Lomond Stadial or between the Stadial and the Flandrian (chapter 7), but it is yet to be established that these horizons are in fact synchronous, and there is evidence to suggest that biostratigraphic response to the climatic deterioration of the Loch Lomond Stadial or to the climatic amelioration of the Flandrian may have been quite variable in time throughout Scotland (see chapter 9). However, assuming that major biostratigraphic horizons are more or less synchronous within the limited study area, and accepting the assemblage zone correlation table of Chapter 7, then a number of ecological inferences can be made for the Lateglacial period in southern Perthshire.

Ecological inferences are, however, dependent on a valid reconstruction of the past flora from quantitative palynological data, and the interpretation of this quantitative data is far from straightforward. In chapter 5 a number of the basic problems in lithostratigraphic and biostratigraphic interpretation were reviewed, but even if these difficulties can be adequately taken into consideration or dismissed from the pollen spectra there is still the problem of "interpreting" the numerical data. As a result of the great variation between taxa in pollen production and dispersal (Faegri and Iversen, 1964) it cannot be assumed that the frequency of the pollen of a given taxon is roughly proportional to the abundance of that taxon in the local or regional vegetation. A number of taxa that may have been very common during the Lateglacial are poorly represented in the pollen spectra (Birks, 1973), and the reduction in percentage of a particular taxon in the pollen profile may relate directly to a reduction of ground cover or in flowering ability of that particular taxon, or may simply be a statistical result of the immigration of a more liberal pollen producer into the local area.

Thus it is difficult to reconstruct the composition of the vegetation for any particular period and to assess the spatial and temporal distribution of taxa. The following restrictions on the present study, based entirely on relative pollen frequencies, enforce a simple inferential approach to the interpretation of the pollen diagrams.

(1) Most of the identifications in this study are to genus or family level, and thus most of the taxonomic divisions cover a broad ecological background, particularly with the pollen types grouped under Gramineae, Cyperaceae, Ericaceae, Compositae, and Caryophyllaceae, and with the genera Salix and Empetrum. These taxa were very common in Lateglacial times but can be found today in an extremely wide variety of communities and habitats (McVean and Ratcliffe, 1962). This therefore restricts the pollen spectra as indicators of ecological conditions.

(2) Birks (1973) has suggested that for the correct interpretation of fossil pollen assemblages as indicators of plant communities comparisons should be made with modern pollen assemblages. However, both Birks (op. cit.) and Pennington (1977) argue that some of the fossil pollen spectra of northern Scotland and Skye cannot be matched with any surface pollen assemblages representing present-day

plant communities from Highland Britain, and also that some Lateglacial spectra represent types of vegetation that are not found in northern Europe today. It may be, therefore, that some of the pollen spectra discussed in this chapter were produced from a vegetation cover that has no modern analogue. Added to this are the problems that the spectra may reflect more than one type of plant community, and that part of the pollen rain may be derived from extra-regional sources.

(3) A number of inferential interpretations tend to use recognised 'indicator species', as for instance inferences based on the relative representation of Empetrum or Artemisia and the relationship of these with climatic conditions or relative amount of snow cover (Brown, 1971; Walker, 1975a; Pennington, 1975, 1977). The problem here is that there are extremely few autecological studies on which to base such inferences. Iversen (1964) has pointed to the possibility of ecotype variation during the Lateglacial, and of fundamental importance to our interpretations of the Lateglacial vegetation is the possibility that "... the present ecological tolerances of some species may be broader in the absence of competition than they are in its presence, whereas deficiencies in the habitat requirements of particular species may have been compensated by other environmental factors that do not now operate at the same intensity within the present geographical range of the species ..." (Birks, 1973, p.326).

Thus much caution is required in the interpretation of fossil pollen assemblages, and the approach employed in this chapter is an inferential one based on broad ecological reconstructions, both temporal and spatial, recognising the limited information supplied by relative pollen percentages and lithostratigraphy.

2. THE LATEGLACIAL INTERSTADIAL VEGETATION

The pollen record of the Lateglacial Interstadial can be considered in terms of two phases of vegetational development. An early phase, characterised by a predominance of herbaceous taxa with relatively low percentages of locally-derived pollen of woody plants, can be distinguished in each profile, though the earliest pollen assemblage zones for each site are probably not synchronous. This herbaceous phase, with varying representation of dwarf-shrub components, is represented by pollen zones T2a and T2b (Fig. 17), Tla and Tlb (Fig. 15), Cla-c (Fig. 18), Amla and Amlb (Fig. 20), and Am2a and Am2b (Fig. 22). The second phase represents a more stable and closed vegetation cover with a higher proportion of woody taxa represented, and correspondingly reduced values for pollen of herbaceous plants (zones T2c, Tlc, Cld, Amlc, Am2c).

With the exception of zone T2a (Fig. 17) the characteristic features of the basal local pollen assemblage zone at each site are the extremely low pollen content (see chapter 4), the relatively high values of deteriorated pollen (chapter 6), and the relatively high values of arboreal pollen, particularly of Pinus and Betula (chapters 5 and 7). The woody plant pollen is unlikely to be of local origin, especially where grains of Alnus and Corylus are recorded, and the low pollen influx in the basal zones probably reflects a severely impoverished vegetation at that time. The predominantly minerogenic deposition and high deteriorated pollen counts of these zones also reflect the lack of vegetation cover on surrounding slopes. It is concluded that the low pollen influx (of locally-derived pollen) in the basal assemblage zones tended to produce pollen spectra that emphasise grains derived from long-distance transfer. The low pollen content of the sediments also results in an emphasis of grains derived by contamination in those profiles based on sediments collected by Hiller corer. The following zones are thus considered poor records of contemporary vegetation, except that they indicate that the vegetation could only have been exceedingly sparse: Tla, Cla, Amla, and Am2a.

In the Lateglacial type-profile, Tynaspirit 2, the early Interstadial phase is characterised by high percentages of pollen of Rumex, Thalictrum, Gramineae and Cyperaceae, with Empetrum and Salix also important. Similar assemblages are recorded at Cambusbeg in zones C1b and C1c, though this profile is badly contaminated. It does, however, support the interpretation that early in the Lateglacial Interstadial a predominantly herbaceous vegetation cover, with dwarf-shrub elements locally important, had spread throughout the Teith Valley.

The strong representation of Rumex pollen is a characteristic feature of Lateglacial pollen profiles from Highland Scotland (Vasari and Vasari, 1968; Pennington et al., 1972; Walker, 1975a and b), and this genus is dominant in the early phase of the Lateglacial Interstadial at Cambusbeg and Tynaspirit. Though it has generally been assumed that pollen grains of this genus are attributable to Rumex acetosa or Rumex acetosella, Vasari and Vasari (1968) found from an analysis of fossil Rumex fruits from Aberdeenshire that the majority of the fruits were of R. tenuifolius. Whether this singular macrofossil study can be extended to apply to Rumex representation generally in the Scottish Lateglacial is questionable, but given that this evidence indicates that R. tenuifolius was the dominant species then not only does the predominance of Rumex pollen spectra suggest a vegetation of generally open character but also a vegetation cover that was associated with poor, acid conditions. R. tenuifolius has the more northern distribution of the Acetosella group and is likely to grow on poorer, more acid soils than R. acetosella which shows a preference for better soils (Clapham et al., 1962; Vasari and Vasari, 1968). However, Pennington (1977) has recently attributed most of the Lateglacial Rumex pollen identified at Cam Loch, Sutherland to R. type acetosa, and Birks (1973) has recognised a considerable number of grains of Oxyria digyna in Lateglacial sediments in Skye. Pollen of Oxyria are extremely difficult to distinguish from Rumex, and since, like certain species of Rumex, Oxyria digyna is characteristic of open-habitat conditions, flourishing on moist sands and silts and on freshly-exposed substrates, the high percentages of Rumex in the Lateglacial pollen spectra at Cambusbeg and Tynaspirit may include a proportion of Oxyria grains and probably includes pollen of both R. acetosa and R. tenuifolius.

Salix pollen grains have not been quantitatively subdivided into species, but though some grains have been tentatively ascribed to S. type herbacea, most of the Salix grains in the Lateglacial Interstadial spectra are thought to represent shrub-willows. Salix has been recorded on substrates in front of retreating glaciers (Palmer and Miller, 1961; Stork, 1963), and is often associated with high percentages of Rumex pollen in such situations. Pennington (1977) describes pollen spectra from northern Scotland where Salix herbacea pollen are significant in a zone dominated by pollen grains of Rumex. The pollen spectra are interpreted as representing a mosaic of pioneer communities of chionophilous character, with Salix herbacea dominating areas of long snow-lie, and Rumex acetosa and Oxyria digyna thriving on well-drained coarse drift. Comparisons have been made with modern pollen assemblages from surface sediments from a lake in the Jotunheim mountains in S.W. Norway where support is found for this general interpretation (Pennington, 1973). Since Cambusbeg and Tynaspirit lie within extensive ice-sheet sand and gravel deposits, the initial surface following deglaciation would have been a well-drained coarse gravel, suitable for the rapid expansion of Rumex and Oxyria, but since Salix grains could not confidently be attributed to S. herbacea, but rather suggested shrub willows, then the Salix records from the Teith Valley may not reflect long snow-lie but the immigration of shrub willow along the valley floor where soils may have developed more rapidly.

The early Interstadial phase at Cambusbeg and Tynaspirit is also characterised by significant percentages of Galium, Thalictrum, Compositae and Caryophyllaceae, which together with the relatively high percentages of Gramineae and Cyperaceae indicate open vegetation with much bare soil or fresh substrate present and the spectra suggest that basiphilous herbaceous communities were widespread during the early Interstadial phase. It is therefore concluded that these basal spectra reflect initial plant colonisation of bare substrates following the widespread deglaciation of this area from the Late Devensian ice-sheet.

The presence of Empetrum during the early Interstadial phase at Tynaspirit indicates that locally small areas of more stable soils were interspersed with areas of bare minerogenic soils. The presence of Empetrum pollen grains in Lateglacial pollen profiles is usually considered to indicate improving climate (Singh, 1963, 1970) or more stable soil conditions, particularly in the transition phase between Jessen-Godwin zones III and IV (Smith, 1961; Watts, 1963). In the early Interstadial phase it therefore seems that open-habitat herbaceous communities were dominant, but that locally soils developed more quickly and permitted the expansion of Empetrum heath. It is difficult to determine the character of the plant communities present at this time, for the high percentages of Rumex pollen (where they dominate the pollen spectra) and the high percentages of Empetrum without Calluna cannot be matched with any published pollen spectra from Highland Britain today (Birks, 1973; Pennington, 1977). Salix species are associated with a variety of scrub and dwarf shrub communities in Scotland today, and though the Salix lapponum-Luzula sylvatica nodum (Montane willow scrub) of McVean and Ratcliffe (1962) is associated with Rumex acetosa there are no communities today in Scotland that match the Rumiceto-Salicetum lapponae of Rondane (Dahl, 1956). Though the actual species differed in the Lateglacial a Salix-Rumex association may have developed on base-rich soils that resembled these present-day associations now confined to ungrazed crag ledges and damp base-rich soils at high levels. Salix species may also have been associated with 'tall herb' communities in the early Interstadial, resembling the close associations of Sub-alpine willow scrub and 'tall herb' communities, involving a variety of willow shrubs, to be found near the summits of restricted parts of the eastern Grampians. "Vegetation of this type was probably once extensive on damp base-rich soils at higher levels, within the geographical range of these montane willows. Many of the mesotrophic mires and damp grasslands are likely to have carried a willow shrub layer, and there were probably transitions to the lower level communities of Salix aurita and S. atrocinerea" (McVean and Ratcliffe, 1962, p.27).

The only association so far described from Scotland where Empetrum is dominant almost to the exclusion of other ericaceous taxa is McVean and Ratcliffe's Rhacomitreto-Empetretum (Rhacomitrium-Empetrum heath) Association. However, modern pollen counts are not available for this association, and Rhacomitrium spores have not been recognised in the Lateglacial pollen spectra. Recently macrofossil evidence for the widespread development of the terrestrial moss Rhacomitrium lanuginosum with Empetrum heath has been identified in the developing Lateglacial-Flandrian transition flora on Rannoch Moor (Lowe and Walker, in press). Here, too, the presence of Rhacomitrium was not reflected in the microfossil assemblages. Thus it is possible that associations similar to the Rhacomitrium-Empetrum heaths developed in the Teith Valley during the early Interstadial. Such heaths are common today in the northern and western Highlands on block scree or bedrock with immature soils and on level or gently sloping ridges and summits below true Rhacomitrium heaths.

Thus the early Interstadial vegetation of the Teith Valley was probably an intricate mosaic of Empetrum heaths, grassland communities varying in richness of species according to base-status or relative soil development, shrub willow heaths and Rumex-Salix associations, moss heaths, and interspersed with these communities were areas of bare soils or fresh substrate. A moss carpet was probably associated with most, if not all, of the plant communities, and the clubmoss Selaginella (an indicator of soils with high base-status) may have been widespread in areas of bare soil.

By comparison, the early Lateglacial Interstadial pollen spectra from Amulree (zones Am1a and Am1b, Fig. 20; Am2a and Am2b, Fig. 22) suggest a more open vegetation, with a higher representation of taxa indicating disturbed soils or immature minerogenic soils. In addition to relatively high percentages of Rumex, Caryophyllaceae, Compositae, and Ranunculaceae, there are records of Thalictrum, Artemisia, and Helianthemum throughout the Lateglacial Interstadial deposits, and the clubmosses Lycopodium and Selaginella are important components of the early Interstadial spectra. The continuous significant representations of Artemisia, Lycopodium and Selaginella indicate that large areas around Amulree supported a sparse vegetation cover during the early Interstadial. The relatively high percentages of Salix at the base of the profiles (zone Am1a and the basal spectrum in Am2a) may indicate the local presence of Salix herbacea but Salix grains were not identified to species level. The relatively poor representation in the pollen spectra of shrubs indicates that grassland communities (including 'tall herb' or species-rich herb meadows) characterised the area around Amulree in the early Lateglacial Interstadial.

The early Interstadial phase is followed by a phase in which woody taxa were more important in the vegetation. At Tynaspirit and Cambusbeg the early predominantly herbaceous or dwarf-shrub communities are replaced by a vegetation cover in which Betula and Juniperus were dominant components. Herbaceous taxa decline markedly in all three pollen diagrams from the Teith Valley, but the continued representation of herbaceous taxa indicates that there continued to be localised areas of immature soils and open-habitat vegetation. However, the high percentages of Betula and Juniperus pollen indicate the development of more mature and stable soils in the later part of the Interstadial, in association with a closed vegetation cover.

To what extent the high percentages of Betula pollen reflect the local growth of birch woodland remains questionable. Macrofossils of Betula are not available from the sites reported here, but macrofossil finds reported from Lateglacial Interstadial deposits from Aberdeenshire have been attributed mainly to the dwarf birch variety, Betula nana (Vasari and Vasari, 1968). Birks (1973) has recognised macrofossils of Betula pubescens from Lateglacial Interstadial deposits from Skye, and thus it would seem not unlikely that tree birch had spread into the Teith Valley during the Lateglacial Interstadial. Though pollen of Betula have not been quantitatively separated into different species according to the criteria suggested by Terasmae (1951) or Birks (1968), mainly because of the use of Erdtman's acetolysis method in pollen preparations (see chapter 3), on a comparison with Flandrian birch pollen grains identified at these sites the majority of birch grains recorded in the late Interstadial phase appeared to be of tree-birch type. With percentages of birch pollen in excess of 40% of total land pollen at both Tynaspirit and Cambusbeg it thus seems likely that at least copses of birch woodland flourished locally in the late Interstadial. The position of the birch tree-line during the Interstadial is discussed in chapter 9.

The late Interstadial expansion of Juniperus recorded at Cambusbeg and Tynaspirit 2 is not reflected in the pollen spectra of Tynaspirit 1. It is difficult to determine whether this results from statistical errors, as for instance the possibility that a higher rate of Betula pollen influx at Tynaspirit masks the real increase in Juniperus pollen concentration, or whether it indicates local differences in the relative ground cover of Juniperus during the late Interstadial. It is not certain whether Juniperus communis was an important vegetation component during the Interstadial, or whether the increased percentages of Juniperus pollen can be attributed mainly to increased flowering and pollen production by prostrate juniper shrubs (Iversen, 1954). However, it seems likely that the larger shrub variety of juniper was present, for seeds and needles of Juniperus communis have been identified from Lateglacial Interstadial sediments from Aberdeenshire (Vasari and Vasari, 1968). Whatever the physiognomy of the juniper plants present at this time, it is known that species of Juniperus are decidedly heliophytic, and thus the relative importance of Juniperus pollen in Interstadial spectra from different sites may relate to relative suppression of the flowering of juniper as a result of shading by birch trees. The marked differences in the Tynaspirit 1 and Tynaspirit 2 juniper percentages may therefore reflect variation in the density of birch stands between these basins that are only about 100 m apart.

Thus the late Interstadial vegetation in the Teith Valley is characterised by tree and shrub communities, with some grassland and 'tall herb' communities continuing to be locally dominant, perhaps on steeper slopes and in patches of coarser drift deposits. By comparison woody taxa are much less important at Amulree in the late Lateglacial Interstadial phase (zone Am2c - because of the problems of distortion and contamination at Amulree 1, discussed in chapters 4 and 5, attention is here focused on the Amulree 2 diagram). Although _Juniperus_ and _Empetrum_ pollen percentages increase in zone Am2c, they do not suggest that shrub heaths dominated at Amulree, but that they probably existed as scattered shrub stands in a general grassland vegetation cover. Though percentages of _Artemisia_, _Lycopodium_ and _Selaginella_ all decline in zone Am2c, their continued significant representations indicate that areas of bare minerogenic soils resisted a closed vegetation cover throughout the whole of the Lateglacial Interstadial.

The Lateglacial Interstadial pollen spectra from the five Lateglacial profiles indicate that areas of bare or open ground persisted throughout the Interstadial in parts of the Grampians, probably on steeper, higher, or more exposed slopes, and even in lower and relatively sheltered valleys, such as the Teith, areas of grassland interrupted the general cover of shrub heath, and birch trees probably only occurred as copses of woodland, though the density of woodland may have varied quite markedly. The spectra in all of the diagrams suggest a continuous and progressive succession of plant communites throughout the Lateglacial Interstadial. If the radiocarbon dates from Tynaspirit 2 are valid this indicates that colonisation of deglaciated parts of the southern Grampians began by at least 12,750 years ago, and shrub heaths may have become widespread by as early as

12,400 B.P. in the Teith Valley. By c 11,400 B.P. it appears that climate had deteriorated sufficiently to alter significantly the plant communities at Tynaspirit, heralding the advance of the Loch Lomond Readvance glaciers. It is suggested, on the basis of the Tynaspirit radiocarbon dates and the character of the Lateglacial Interstadial pollen spectra in the five Lateglacial pollen profiles, that vegetational succession and soil development progressed without interruption from the decay of the Late Devensian ice-sheet (c 13,000 years ago - see chapter 9) until the beginning of the Loch Lomond Stadial. There is no evidence from any of the profiles discussed here of an equivalent climatic set-back to that of the Bölling oscillation, such as has been recently identified in Scottish profiles by Pennington (1975) and Vasari (1977).

The trend towards a closed vegetation cover and eventual soil stability within the Lateglacial Interstadial is reflected not only in the pollen record but also in the basin sediments and in the degree of pollen preservation. At Tynaspirit 1 and Tynaspirit 2 minerogenic sediments characterise the early Interstadial phase, but these give way to organic sediments dated to the later phase of the Interstadial. The presence of minerogenic sediments at the base of the profiles reflects the inwash of fine minerogenic particles from bare mineral soils. The transition to organic sediments reflects firstly, the inwash of organic particles from developing vegetation on surrounding slopes, which is interdependent with the cessation of minerogenic inwash resulting from the production of a closed vegetation cover, and secondly, the accumulation of organic detritus derived from decaying vegetation, phytoplankton and associated fauna within the lake basin.

The lack of development of an organic horizon representing the late Interstadial at Cambusbeg is difficult to explain but has been discussed in chapter 5. The lack of Lateglacial organic sediments at Amulree probably reflects the absence of a widespread closed vegetation cover in the vicinity of the Sma' Glen at any time in the Lateglacial. It is probable that the impoverished nature of the Interstadial vegetation, together with the steepness of the slopes around the basin, the large size of the original lake at Amulree, and the likelihood of a virtual absence of macrophytic vegetation within the lake, were all contributory factors leading to the uninterrupted deposition of minerogenic sediments during the Lateglacial Interstadial.

The general trend towards soil stability in the Interstadial is reflected in the degree of pollen preservation, for at Cambusbeg and Tynaspirit 1 and 2 as well as at Amulree 2 the decline in percentages of total deteriorated pollen from high values in the early Lateglacial Interstadial sediments to much lower percentages in the sediments of late Lateglacial Interstadial age reflects a significant decrease in the amount of sediment inwash into the basins from the surrounding catchments. Most of the deteriorated pollen recorded from Lateglacial sediments is of the broken and crumpled categories (chapter 6). Thus deterioration is mainly a result of physical processes, reflecting predominantly transport of pollen grains. The higher values for deteriorated pollen percentages throughout the Lateglacial Interstadial at Amulree (reflected especially in the Amulree 1 pollen diagram), which contrast with the percentages recorded at the lowland sites near Callander, emphasise the harsher Lateglacial environment at the more exposed upland site, which resulted in poorer soil conditions, a more impoverished vegetation, and the continuation of soil disturbance and therefore inwash of pollen from the slopes in the catchment.

3. THE LOCH LOMOND STADIAL VEGETATION

Following the series of pollen spectra that indicate progressively developing vegetation during the Lateglacial Interstadial, a clear revertence phase is represented in each of the five Lateglacial pollen diagrams. Radiocarbon dates from Tynaspirit 2 place this phase to between 11,400 and 10,400 years ago, and it is thus equated with the Loch Lomond

Stadial, named after the Loch Lomond Readvance (Sissons, 1974a; 1976a). Sediments of Stadial age are characterised by much reduced pollen content, markedly lower percentages of pollen of woody taxa, and by much increased representations of open-habitat taxa in comparison to spectra of Interstadial age. Pollen of Gramineae, Cyperaceae, Rumex and Artemisia dominate the spectra, and these are associated with significant percentages of Caryophyllaceae, Compositae, Thalictrum, and, especially at Amulree, Lycopodium and Selaginella. These assemblages indicate that a widespread and severe break-up of the vegetation cover that had developed during the Interstadial occurred during the Stadial, probably related to severe disturbance of soils.

Vegetation revertence is most marked in the Teith Valley sites, since in these sites a phase of dominant woody taxa is recorded in the Interstadial sediments. Because of the high degree of contamination associated with the Tynaspirit 1 and Cambusbeg diagrams the inferred character of the Stadial vegetation is mainly based on the Tynaspirit 2 diagram. In this diagram marked reductions in percentages of woody taxa occur, with Empetrum almost disappearing from the spectra, and Betula declining from percentages in excess of 40% to less than 5% of total land pollen. Juniperus values also decline markedly at the T2c/T2d pollen zone boundary, but very high percentages are recorded within the upper Stadial deposits. It is unfortunate that continuous analyses are not available for the Stadial sediments at this site, for the full extent of assemblage changes may not be represented, and the beginning of this upper Stadial Juniperus phase is not recorded. The high Juniperus values are problematical, and are discussed more fully in the following section.

Percentages for the woody taxa Pinus and Salix on the other hand actually increase within the Stadial sediments. The increased percentages of Pinus are interpreted as a reflection of pollen derived from long distance transfer which are over-represented in the pollen spectra as a result of the lowered local pollen influx values during the Stadial. In this respect the Stadial spectra thus resemble early Interstadial spectra. The increased _Salix_ percentages are considered to reflect the local expansion or immigration of _Salix herbacea_, as a number of pollen grains from the Stadial sediments of Tynaspirit 2 were tentatively assigned to this species.

While the relatively high percentages of Gramineae, Cyperaceae and herbaceous pollen in general suggest that the dominant vegetation cover of the Teith Valley during the Loch Lomond Stadial was composed of species-rich grassland or herb meadow communities, with perhaps extremely localised growth of dwarf shrubs of _Salix_, _Juniperus_, and _Betula nana_, the significant records of _Artemisia_, _Lycopodium_ and _Selaginella_, together with _Galium_, _Thalictrum_, Ranunculaceae, and Caryophyllaceae, suggest that large areas of bare minerogenic soils also existed in this area at this time. The highest percentages of _Artemisia_, _Lycopodium_ and _Selaginella_ in each of the three Lateglacial pollen profiles from the Teith Valley are recorded in the Stadial sediments, and this may attest the harshness of the climate and the severity of soil disturbance during this period.

It is difficult to interpret the pollen assemblages in terms of present-day plant associations. The taxonomic divisions in the pollen diagrams are in most cases ecologically wide, especially where identification of pollen grains has been to family level only. Also no contemporary pollen spectra have been found with the excessive _Artemisia_ pollen percentages that characterise Loch Lomond Stadial deposits. The pollen spectra from the Teith Valley Stadial deposits could relate to a large number of associations described collectively under 'Montane Grass Heaths', and 'Herb and Fern Meadows' by McVean and Ratcliffe (1962). The Low-alpine grass heath, Tall Herb _nodum_, and Dwarf Herb _nodum_ are likely to be represented, and it is possible that some snow-bed communities, such as the _Cryptogrammeto-Athyrietum chionophilum_ and the Snow-Bed Heaths were also characteristic of the Stadial vegetation. The relatively important representations of _Lycopodium_ and _Selaginella_, together with Cyperaceae and Salix herbacea, may reflect the presence of a snow-bed fern association comparable with the Cryptogrammeto-Athyrietum chionophilum Association characteristic of areas of late snow-lie in the Cairngorms today (McVean and Ratcliffe, 1962). More precise interpretations of the Stadial spectra must await identifications to species level of the pollen assemblages at Tynaspirit 2. A further difficulty is the lack of representation and recognition of moss spores, so that although the existence of moss heaths during the Stadial would seem highly likely, they are not represented in the fossil spore assemblages (see discussion of representation of Rhacomitrium lanuginosum in section 2 above).

A further characteristic of Stadial pollen spectra is the virtual exclusion of pollen of aquatic taxa. In Tynaspirit 2 a marked decline in aquatic pollen percentages occurs at the pollen zone T2b/T2c boundary, below the lower boundary (T2c/T2d) of the Loch Lomond Stadial. Iversen (1964) has pointed out that aquatic plants react much more rapidly to thermal climatic changes than do terrestrial flora, and since changes in percentages of aquatic flora are often interpreted as indicating critical temperature thresholds (Vasari and Vasari, 1968; Walker, 1975a) this may have an important bearing on climatic implications based on the Tynaspirit 2 pollen spectra. Marked changes in aquatic flora can also result from changes in the base-status of lake waters (Vasari and Vasari, 1968; Pennington et al., 1972), but since aquatic pollen percentages remain low throughout the Stadial period, when minerogenic sedimentation occurred, the reduced representation of an aquatic flora is thought to reflect a thermal control. However, rapid sedimentation may also have resulted in water strongly clouded by material in suspension, thus reducing the amount of light available to submerged macrophytes which would provide a second explanation for their absence.

Though a closed vegetation cover did not develop during the late Lateglacial Interstadial at Amulree, and woody taxa are much more poorly represented in the pollen spectra than in the pollen profiles from the

Teith Valley sites, the Stadial revertence phase is nevertheless clearly represented in both Amulree 1 and Amulree 2 (Figs. 20 and 22). At Amulree 2 the Stadial is represented by two pollen zones, Am2d and Am2e. Zone Am2d is characterised by marked increases in Lycopodium and Selaginella spores, and Am2e by increased percentages of Artemisia and Caryophyllaceae.

As in the Teith Valley sites, percentages of Empetrum and Juniperus pollen decline in the Stadial spectra, and they become quite insignificant at Amulree 2. Salix percentages increase significantly, and at this site too a number of grains were tentatively assigned to Salix herbacea. The increased percentages of Betula and Pinus are interpreted as indicating grains derived by long-distance transfer. Whereas at Tynaspirit and Cambusbeg the highest percentages of Rumex characterise the early Interstadial and Loch Lomond Stadial sediments, at Amulree the highest Rumex percentages occur in the late Interstadial sediments, and this taxon becomes less important in the Stadial pollen zones.

The Amulree Stadial pollen spectra are dominated by herbaceous pollen, with percentages of total herbaceous pollen (excluding Gramineae and Cyperaceae) of up to 60% of total land pollen. By far the most important herbaceous taxa are Artemisia and Caryophyllaceae, but other taxa, including Saxifragaceae, Armeria, Epilobium, Helianthemum and Valeriana are much more important in the Stadial spectra at Amulree than in the Teith Valley profiles. Lycopodium and Selaginella percentages are also significantly higher. The slopes around the Amulree basin must have been characterised by open-habitat plant communities, but more commonly by bare mineral soils with little vegetation, and they would thus have been affected easily by sheet erosion and creep processes.

The reduced importance of grasses in the Stadial sediments of Amulree 2, and the predominantly herbaceous pollen assemblages suggest that these pollen spectra reflect communities that have affinities with present-day 'tall herb' communities, 'Dwarf Herb' communities, and also possibly moss heaths. It seems likely that fern-dominated snow-bed communities, akin to the Cryptogrammeto-Athyrietum chionophilum Association, accounted for a greater ground cover around Amulree than in the Teith Valley at any time in the Lateglacial. As explained above, it is difficult to determine with any accuracy the type of associations represented in the pollen spectra, and this is equally true of Stadial spectra, but the records of Saxifragaceae from the Amulree Stadial deposits perhaps provide a clue to some of the plant communities present. The Saxifrageto-Agrosto-Festucetum Association described by McVean and Ratcliffe (1962) is a community characteristically including Saxifraga spp., Ranunculus spp., Cyperaceae genera, Selaginella selaginoides and genera of Gramineae. All of these are included quite commonly in the Stadial spectra. The recognition of Saxifraga aizoides pollen from the Lateglacial spectra of Amulree 2 may also suggest the presence of a comparable association to the Saxifragetum-aizoidis Association, which also includes Selaginella selaginoides, Ranunculaceae, and Polygonaceae.

Thus it would appear that the Stadial spectra from Amulree reflect types of plant associations that are today limited to steep slopes usually in areas of calcareous soils, and on cliffs or steep banks in the Scottish Highlands. The Saxifragetum associations particularly are today confined to steep rocky ground, and usually require wet, silty soils, though often they may overlie the rock surface almost directly. For the Saxifragetum-aizoidis Association "A copious seepage of water down the rock face is as essential as the high lime content of the rock. The association occurs most often on north-facing cliffs since these tend to be the wettest ..." (McVean and Ratcliffe, 1962, p.87). The steep slopes that surround the Amulree basin, at a time when frequent snow-melt may have provided copious water seepage flowing over bare mineral soils, may have provided suitable habitats for this type of association, though whether or not the local schistose-grits or mica-schists would have provided a substrate with a sufficiently high lime content is unknown.

In all of the Lateglacial pollen profiles there is thus evidence of a major set-back to the progression of the plant successions established in the Lateglacial Interstadial, and for the consequent disturbance of soils. This is also reflected in the sedimentary records from Tynaspirit 1 and Tynaspirit 2. In both basins the rich organic deposits that had accumulated during the Lateglacial Interstadial give way to minerogenic Stadial sediments. These consist of stiff grey clays (which probably also include silt fractions) that have very little organic content, and this reflects both the lack of a rich terrestrial flora and an absence of macrophytic aquatic vegetation, as well as the inwash of clay and silt particles from the disturbed soils of the surrounding slopes. The change from stiff clays to the soft Stadial clays (lithostratigraphic unit 4 - Fig. 22) at Amulree 2 is not readily understood.

A further indication of the disturbance of soils and vegetation during the Loch Lomond Stadial is supplied by the deteriorated pollen data. The inwash of soil particles is reflected in two ways by these data. First, in all of the Lateglacial profiles there is a marked increase in the total percentages of deteriorated pollen recorded in the Stadial spectra. The relatively high representation of deteriorated pollen in early Lateglacial Interstadial spectra, followed by a marked reduction of percentages in the late Interstadial, in turn followed by a return to relatively high percentages in the Loch Lomond Stadial spectra, is a pattern common to each of the Lateglacial pollen profiles (Fig. 33). Most of the deterioration is accounted for by physical modifications (breakage and crumpling - Fig. 34), and this is interpreted as reflecting the transport of pollen through streams to the basins during a period of increased erosional activity. Secondly, a small but significant increase in the proportion of corroded pollen can be detected in the Stadial spectra (Fig. 34). This is unusual for Lateglacial spectra, and it is suggested that this reflects the inwash of pollen grains previously trapped in the surface organic mat of soils that had developed during the Lateglacial Interstadial, and which were disturbed by surface wash or frost heaving during the harsher Stadial conditions.

4. VEGETATIONAL DEVELOPMENTS DURING THE LOCH LOMOND STADIAL/FLANDRIAN TRANSITION

In each of the Lateglacial profiles the Lateglacial/Flandrian transition is characterised by a sharp boundary between minerogenic and organic sediments, by a marked decline in percentages of deteriorated pollen to the lowest values in the profiles (see Fig. 33 and chapter 6), by the disappearance from the pollen spectra of many herbaceous taxa, particularly those indicating skeletal or disturbed soils, and by a marked peak in the _Juniperus_ pollen curve followed closely by a rise in the _Betula_ pollen curve to the highest percentages of _Betula_ in each diagram. If the radiocarbon dates are to be believed (see below) then it would appear that a dramatic expansion of juniper heath occurred at the close of the Loch Lomond Stadial, and this was closely followed by the widespread expansion of birch woodland. At the same time soil inwash virtually ceased and more stable soil conditions ensued. Two important aspects of the pollen profiles presented in this thesis, which point to the great environmental changes that took place in this relatively limited period of time, are first, that the expansion of juniper heath and birch woodland is recorded in all of the profiles, indicating that a closed vegetation cover and stable soils developed on both upland exposed localities and in lowland sheltered situations, and second, that the expansion of juniper heath and birch woodland at Amulree during the Lateglacial/Flandrian transition can be contrasted with the inability of juniper and birch to spread into this area during the comparatively long Lateglacial Interstadial.

It may be that climatic factors prevented the immigration of juniper and birch to Amulree during the late Lateglacial Interstadial, and this point is returned to in section 6 of this chapter, but an additional characteristic of Lateglacial-early Flandrian pollen profiles is relevant here. Aquatic pollen percentages increase markedly in each profile in the Lateglacial/Flandrian transition period, and this is most marked in the quantitatively more reliable sites of Tynaspirit 2 (zone T2e, Fig. 17) and Amulree 2 (zone Am2g, Fig. 22). As Iversen (1964) has pointed out, aquatic plants reach much more quickly to climatic change than terrestrial flora. Thus the sharp increases in aquatic pollen percentages recorded in the sites from the Teith Valley and Amulree, together with the other profile characteristics (lithostratigraphic and biostratigraphic listed above), suggest sudden environmental changes in Perthshire during this period.

As outlined in chapter 7 (section 4), it is difficult to interpret and correlate the transition zones from the Lateglacial pollen profiles discussed above. The most detailed record for vegetational developments during this period is provided in the Mollands pollen diagram (Fig. 25), and it is suggested that a sequence comparable to that reflected in the Mollands pollen spectra would have developed at each of the Lateglacial sites, but that parts of this sequence may be masked due to a combination of local site factors, and also to the rapidity of environmental changes at this time. A detailed lithostratigraphic and biostratigraphic record from Mollands (chapters 4 and 7) indicates a transition from unstable to stable soil conditions, and a progressive vegetational succession from open herbaceous grassland communities, followed by dwarf-shrub communities, mixed juniper and birch scrub, and finally by the expansion of birch woodland (zones Moa to Moc, Fig. 25).

A low local pollen influx and unstable soil conditions are indicated in zone Moa at Mollands, first by the high counts of *Pinus* pollen recorded, reflecting over-representation of pollen grains derived by long distance transfer, secondly by the relatively high percentages of Compositae, Saxifragaceae, *Artemisia*, *Rumex*, *Selaginella* and *Lycopodium* (including *L. selago*), thirdly by the high influx of deteriorated pollen grains and spores, and fourthly by the predominantly minerogenic sediments. In subsequent zones there is a gradual transition to organic sedimentation, reduction in the representation of deteriorated pollen and spores, and the final disappearance or at least marked reduction in percentages of a number of herbaceous taxa. The pollen diagram indicates a progressive succession of plant communities at Mollands, with the establishment of dominant birch woodland and the immigration of the relatively thermophilous Corylus shrub in zone Moc.

The basal zone Moa in some ways resembles pollen assemblages from the early Lateglacial Interstadial, in that a predominant vegetation of species-rich grassland is suggested by the spectra, which include basiphilous elements such as Thalictrum and Galium. This is consistent with the hypothesis that the earliest spectra at Mollands reflect colonisation of bare substrate following deglaciation in this area. Plant communities that have been described from early colonisation phases of freshly-exposed substrates in front of retreating glaciers characteristically include species of Compositae, Saxifragaceae, Artemisia, Selaginella, Lycopodium and Rumex, often in association with shrubs of Salix (Crocker and Dickson, 1957; Stork, 1963). As stated earlier (this chapter), relatively high percentages of Rumex may also include pollen of Oxyria digyna, and both Oxyria and Rumex are common pioneer species on freshly-exposed substrates at the present time (Persson, 1964). The basal spectra at Mollands are thus interpreted as indicating a colonisation phase of bare substrate, freshly-exposed by the retreating Teith Valley Loch Lomond Readvance glacier.

The relatively high representation of Salix in zone Moa may represent the local presence of Salix herbacea, which would fit with the suggestion of a colonising flora. However, no grains were even tentatively assigned to S. herbacea from this site, and it is thought that the Salix pollen increase probably represents the association of dwarf willow shrubs with grassland communities, resembling associations to be found on the summits of the Cairngorms today (McVean and Ratcliffe, 1962). The dominant Empetrum phase that followed (zone Moa III) may reflect communities that resembled McVean and Ratcliffe's Rhacomitreto-Empetretum Association (see discussion of early Lateglacial Interstadial flora above), and the dominant Juniperus phase (zone Mob II) must represent extreme local over-representation of Juniperus pollen. With such excessive relative percentages of Juniperus it is highly unlikely that this represents transfer of juniper grains from plants flourishing in other parts of the Teith Valley, at least not solely, but that it indicates immigration of juniper into the Mollands catchment.

One particular pollen curve that is of importance at this site is that of Betula nana. More confidence could be placed in recognitions of B. nana at this site because of unusually distinctive pore outlines to some grains, these being noticeably more angular than pores of the generally similar tree birch grains that had been identified from Mollands and from other sites. It can be seen that a peak in Betula nana pollen coincides with the peak in Juniperus at this site. This is thought to represent the local growth of dwarf birch, and it is possible that prostrate or dwarf juniper was also initially important as well as tall shrub juniper at this site. Thus the curve for Betula (undifferentiated) may indicate grains derived by aerial transport from birch stands farther down valley, at least in zone Moa, for it is unlikely that tree birch grew in the immediate vicinity of Mollands until after the immigration of shrubs, recorded in zone Mob.

A marked increase in juniper pollen percentages has been interpreted as an immediate response to thermal improvement by juniper already present in an area (Iversen, 1954; Pennington, 1975), and thus the marked Juniperus rise at Mollands could be interpreted in this way. This is thought unlikely, however, for the rise in juniper is more likely to reflect immigration of juniper onto local slopes, probably delayed in comparison to areas around Cambusbeg and Tynaspirit because of the time-lag in pedogenesis in a newly-deglaciated area. The climatic improvement that took place in the Lateglacial/Flandrian transition may be more precisely recorded by the expansion of aquatic pollen percentages in zone MoaI (Iversen, 1964). No direct comparisons can be made of pollen assemblages recorded from the Lateglacial/Flandrian transition from Mollands with corresponding assemblages from Cambusbeg and Tynaspirit. It may be that soils at Cambusbeg and Tynaspirit, which were not covered by Loch Lomond Readvance ice, were only partially destroyed by frost disturbance during the Loch Lomond Stadial, and thus immigration of shrubs and birch trees may have been more rapid at these sites in comparison to the local slopes around the Möllands basin where time must be allowed for soil to develop from an initially bare substrate.

The continued representation of herbaceous taxa, especially Rumex, Lycopodium selago, Compositae and Saxifragaceae, into sub-zone Mob II probably reflects the continued presence of bare mineral soils within localised parts of the Mollands catchment, especially on the steeper slopes that are north-facing. On the other hand, the continued representation of Cyperaceae, Ranunculaceae, Rosaceae, and Taraxacum, and the marked increased representations of Umbelliferae, Valeriana, Filicales and Dryopteris at the sub-zone Mob II/Mob III boundary, are likely to reflect the expansion of reedswamp around the edge of the basin. It is extremely difficult to determine to what extent herbaceous taxa represented in the pollen assemblages reflect local open-habitat communities in the regional vegetation, and to what extent they may reflect communities of the local reedswamp vegetation that develop as a natural early stage in the local hydrosere. This is especially difficult where non-specific pollen determinations characterise the pollen assemblages, as in the present study.

Radiocarbon-dating of the Mollands profile suggests that the dwarf-shrub phase was established as early as 10,670 ± 85 B.P., and that a mixed juniper-birch heath had become established by 10,480 ± 150 B.P. These dates are considerably older than radiocarbon age determinations of the Lateglacial/Flandrian boundary at other sites in Highland Britain (Godwin and Willis, 1959, 1964; Shotton et al., 1970; Sissons and Walker, 1974; Vasari, 1977), and a full discussion of their relevance is given in chapter 9. However, dates from Tynaspirit 2 and Amulree 2 would seem to support the dates from Mollands. At Amulree 2 (Fig. 22) the expansion of dwarf-shrub communities that marks the close of the harsh environment of the Loch Lomond Stadial occurred by 10,770 ± 90 B.P., and juniper heath became established at about 10,270 ± 100 B.P. At Tynaspirit 2 (Fig. 17) no date is available for the dwarf-shrub phase, but the juniper expansion here is dated to 10,420 ± 160 B.P. If the radiocarbon dates are correct, then they indicate first of all the establishment of widespread dominant heath communities in Scotland, especially juniper, much earlier than previously supposed, and secondly, that the succession from open grassland to juniper heath during the Lateglacial/Flandrian transition period occurred in less than 500 years in lowland sites (Mollands, Tynaspirit) and in upland sites (Amulree) of the Grampians. This vegetational transition appears to have been particularly rapid in the Teith Valley.

One anomalous feature in the Lateglacial/Flandrian transition deposits presented in this thesis is the peak in Juniperus pollen that occurs in the upper part of zone T2d (Fig. 17). Since this pollen diagram is based on samples collected by enlarged piston corer, sampling contamination is thought unlikely. This particular juniper peak appears anomalous for it coincides with pollen predominantly of open-habitat taxa, and there is no corresponding increased representation of any other woody taxa in the diagram. In a relative percentage pollen diagram such isolated peaks are sometimes particularly difficult to explain, but if juniper did manage to survive during the Loch Lomond Stadial in the Teith Valley (see chapters 3 and 7) then the marked peak of juniper pollen in zone T2d may relate to increased flowering of juniper shrubs already present in the area around Tynaspirit. Thus the following three-fold explanation is advanced for pollen frequency variation in zones T2d to T2f:

(i) Relatively high percentages of juniper pollen in the upper part of zone T2d, reflecting increased flowering of juniper shrubs already present in the area, probably represent an immediate reaction to increased temperatures. Since local pollen influx would have been low at this time, this could result in gross over-representation of juniper in terms of its relative ground cover in the surrounding vegetation.

(ii) As grasslands and Empetrum heaths expanded in the area, replacing moss heaths and colonising exposed surfaces and disturbed soils (see section 9, chapter 10), the increased influx of Gramineae, Cyperaceae, and Empetrum pollen (and pollen of other herbaceous species) would result in lower relative percentages of Juniperus (zone T2e).

(iii) With the gradual increasing stability of soils, juniper heaths would then also have been able to expand in the area, eventually becoming dominant in the local vegetation. This might therefore explain the second peak in juniper pollen percentages at the T2e/T2f transition.

Absolute counts of pollen and spores are required in order to test the validity of this hypothesis. However, if this explanation is correct, then this would indicate some divergence between climato-stratigraphic and biostratigraphic horizons in the Tynaspirit 2 profile.

5. IMPLICATIONS OF THE POLLEN RECORDS AND RADIOCARBON DATES FOR THE GLACIAL SEQUENCE IN PERTHSHIRE

The sites described in this thesis are critically related with respect to Late Devensian glacial deposits and limits recognised in Perthshire (Simpson, 1933; Charlesworth, 1955; Francis et al., 1970; Thompson, 1972) and thus the sediments and pollen spectra preserved in these basins contain important data for the glacial sequence in this area. Cambusbeg, Tynaspirit 1 and Tynaspirit 2 are kettle-holes within widespread fluvio-glacial deposits. Since the basal deposits at each of these sites have been shown by pollen analysis and radiocarbon dating to be of Lateglacial

Interstadial age then the fluvioglacial landforms in this area must be the product of the decay of the Late Devensian ice-sheet. The identification of Lateglacial Interstadial deposits within the Amulree basin also dates the large hummocks that surround this site to earlier than the Loch Lomond Readvance of glaciers, and thus to ice-sheet decay.

Thus the pollen profiles described here support Thompson's contention (1972) that the Loch Lomond Readvance glaciers did not extend beyond Callander in the Teith Valley and did not extend into the valley of the Girron Burn north of Newton in Glen Almond (Figs. 5 and 6). Francis et al., (1970) suggested a Lateglacial readvance limit at Drumvaich, midway between Callander and Doune (4 km downvalley from Callander). Thompson could find no morphological evidence for such a readvance limit, and the radiocarbon dates from Tynaspirit imply that no glacial readvance took place after 12,750 B.P. beyond the locality of Callander.

If the basal radiocarbon date from Tynaspirit 2 is correct then a minimal date for the disappearance of the Late Devensian ice-sheet in southern Perthshire is 12,750 ± 120 B.P. This date is minimal for several possible reasons. First, it is possible that dead ice could have survived in the Tynaspirit kettle hole for some time after the general deglaciation of the Teith Valley (cf. Porter and Carson, 1971). Secondly, there may also have been some time-lag between deglaciation of the Tynaspirit kettle-hole and consequent initiation of sediment accumulation. Thirdly, there are several centimetres of minerogenic sediments below the dated basal horizon. However, it is currently suspected (R.E.G. Williams, pers. comm.) that dates based on gyttja material may be older than the true age of the material. This date is compared with other early Lateglacial radiocarbon dates from Scotland in chapter 9.

Thompson (1972) has identified a number of Loch Lomond Readvance limits in south and west Perthshire (Fig. 5). Most of these are defined by downvalley limits of hummocky moraine, such limits having a varying degree of clarity, but the limit within the Teith Valley is marked by a clear terminal moraine. Only two basins that provided suitable material for pollen analysis and radiocarbon dating have been located within the Loch Lomond Readvance limits, despite a thorough search of quite extensive areas (see chapter 2). No Lateglacial Interstadial deposits have been found in these two basins, but the earliest deposits (Mollands, Fig. 25) are attributed to the Lateglacial/Flandrian transition. This of itself does not prove that the glacial limits identified by Thompson are of Loch Lomond Stadial age, but would certainly seem to provide support for his hypothesis.

The strongest evidence for the dating of a Loch Lomond Readvance limit is that of the terminal moraine at Callander. Only about 2 km downvalley from the terminal moraine (Fig. 6) are three kettle-holes that contain Lateglacial Interstadial deposits. Immediately within the moraine, at Mollands, a deep kettle-hole contains only Lateglacial/Flandrian transition and Flandrian deposits. The variation in sediments, in pollen content and the pollen assemblage records at Mollands would fit a hypothesis of deglaciation of this basin followed by gradual stabilisation of soils on surrounding slopes (chapters 4 and 7). The radiocarbon date of the basal Mollands deposits is 10,670 ± 85 B.P., and the date of the Lateglacial/ Flandrian transition juniper phase at this site, 10,480 ± 150 B.P., agrees well with the date for the equivalent biostratigraphic horizon at Tynaspirit 2, <u>viz</u>. 10,420 ± 160 B.P. The most straightforward explanation of the glacial deposits and biostratigraphic records in the Teith Valley is that which envisages the Callander terminal moraine as being of Loch Lomond Stadial age, and the Mollands basin as representing the development of a kettle-hole within Loch Lomond Readvance deposits.

The basal radiocarbon date from Mollands indicates retreat of the Loch Lomond Readvance glaciers in southern Perthshire by possibly as early, or even earlier than, 10,700 B.P. This is much earlier than the conventional age for the decay of the Loch Lomond Readvance glaciers, and is almost as early as the conventional lower boundary of the "Zone III period" (10,800

B.P.; see Sissons, 1967a; 1976a.) If radiocarbon dates had been available for only one site, for example Mollands, then they probably would have been dismissed as contaminated or in error for some other reason. However, dates from Tynaspirit 2 (10,420 ± 160 B.P.) and Amulree (10,770 ± 90 B.P.) support the date from Mollands and suggest at least the possibility of alternative explanations. These dates are discussed along with a review of available Lateglacial/Flandrian transition dates from Scotland in chapter 9, but the possibility is introduced here that, if the radiocarbon dates are valid, either deglaciation from the Loch Lomond Readvance glaciers was much earlier in general than previously supposed, or this deglaciation was widely time-transgressive, and occurred much earlier in, for instance, parts of Perthshire than in other parts of Scotland.

6. IMPLICATIONS OF THE POLLEN RECORDS AND RADIOCARBON DATES FOR CLIMATIC DEVELOPMENTS IN PERTHSHIRE

The pollen records presented in this thesis provide evidence of only one vegetational revertence phase, equated with the Loch Lomond Stadial. The sequence of pollen zones from Lateglacial Interstadial deposits is at each site interpreted as indicating a seemingly uninterrupted vegetational succession throughout this period, from open herbaceous grassland communities with basiphilous components, to closed vegetation (at least in the lower sites of the Teith Valley) of dwarf-shrub heath with occasional birch copses. According to the radiocarbon dates from Tynaspirit 2 there appears to have been conditions suitable for continuous immigration of woody plants and soil stabilisation from about 12,750 B.P. until at least 11,400 B.P., and possibly as late as 11,100 B.P. The rather large standard deviation associated with the upper Lateglacial Interstadial date at Tynaspirit 2 (11,385 ± 290 B.P.) means that this date does not critically delimit the age of vegetation and soil disturbance at this site (see chapter 9).

This time period spans the chronozone boundaries of the Bölling and Older Dryas episodes in the stratigraphy of continental north-west Europe (Mangerud et al., 1974), with chronostratigraphic definitions based on the recognition of a distinct climatic oscillation within that part of the Late Weichselian stratigraphy that equates with the Lateglacial Interstadial as defined in this thesis. There is thus no evidence from any of the Lateglacial profiles presented here of an equivalent to the Bölling oscillation. There is the possibility that because the spectra are based on relative pollen percentages this oscillation is masked in the diagrams: this would occur especially if the oscillation was weak or short-lived. Recent evidence from northern Scotland (Pennington, 1975) suggests that a minor climatic recession can be detected within the Lateglacial Interstadial where absolute pollen analysis techniques are employed. Whether this can be detected generally throughout Scotland, or whether it can only be detected from critically located sites (see chapter 9) requires further investigations. It would seem that any climatic oscillation that occurred within the Lateglacial Interstadial was either of small amplitude or of very short duration, at least in the context of southern Perthshire, and was relatively insignificant when compared with the overall climatic amplitude of the Lateglacial Interstadial.

It is extremely difficult to establish thermal parameters from palaeobotanical data. Necessary detailed autecological studies are rare, and usually indicate taxa or communities as having a wide range of ecological and climatic tolerances. It is therefore perhaps not surprising that gross errors have been made in the past in attempting to reconstruct climatic characteristics of the Lateglacial period from a knowledge of paleobotany alone (Coope, 1970, 1975). In view of recent demonstrations of contrasting ecological inferences between fossil faunal assemblages and floral assemblages for the same time period in south-west Scotland (Bishop and Coope, 1977) only extremely generalised inferential conclusions concerning Lateglacial climate can be based on pollen records.

The relatively high percentages of Betula and Juniperus pollen in the late Lateglacial Interstadial phase at Tynaspirit 2 (see section 2, this chapter) indicates that temperatures were warm enough to permit the immigration and growth of juniper heath and birch copse for most of the Lateglacial Interstadial, at least until about 11,400 B.P., and perhaps until about 11,100 B.P. No indication of overall variation of temperature for the Lateglacial Interstadial period can be determined from palaeobotanical records alone. However, it has been suggested by Iversen (1954) that the presence of Betula pubescens in the local flora implies a mean July temperature of at least 12°C. It is not certain that the birch pollen recorded at Tynaspirit 2 were of Betula pubescens, but the majority can confidently be attributed to tree birch. Macrofossil records of Betula pubescens are available from the Isle of Skye (Birks, 1973) and the development of tree birch copses characterises late Lateglacial Interstadial vegetation throughout Scotland (chapter 9), with Betula pubescens the most likely species. It would seem likely that copses of this species existed within the Teith Valley, indicating mean July temperatures of about or in excess of 12°C for most of the Interstadial until at least 11,400 B.P. Further, consistent records of Littorella uniflora (Shore-weed) pollen from the latter part of the Lateglacial Interstadial in Skye have been interpreted as indicating mean July temperatures of 14°C or more for this time (Birks, 1973). It would therefore seem that a mean July temperature of 12°C for the latter part of the Lateglacial Interstadial in southern Perthshire is a conservative estimate. However, little indication can be found from the pollen records of the character of the climate during the early phase of the Lateglacial Interstadial.

The Amulree 2 Lateglacial pollen profile indicates that birch copses did not develop in the valley of the Girron Burn during the Lateglacial Interstadial. The inability of birch to spread into this area could indicate that an important thermal threshold, at least for the later part of the Lateglacial Interstadial, lay between the altitudes of the Teith Valley around Callander and of Amulree. In other words the climatic gradient of that time was such that at about 300 m mean July temperatures were significantly less than 12^{o}C, such that tree birch (and even juniper heath) were unable to immigrate or at least flower profusely at this altitude in the southern Grampians. However, at least two other factors could have been controlling the inability of tree birch to spread throughout the Teith Valley and to immigrate into the Amulree area: the first is the migration rates of trees and shrubs, and the second is the time required for soil development, especially in areas of steeper slopes. Both of these factors, and indeed local climatic parameters, are largely interdependent, and it is this that renders the reconstruction of climatic parameters based on palaeobotanical considerations alone so questionable, especially where limited time periods are involved.

It is difficult, because of the wide ecological differences over short distances in Scotland today, to draw major conclusions regarding climate from the few Lateglacial pollen profiles and the limited study area discussed in this thesis. A more comprehensive approach, involving palynological studies and other evidence from throughout Scotland, is employed in chapter 9. However, there is reason to suggest, from features in the pollen diagrams from southern Perthshire alone, that climatic conditions in the later part of the Lateglacial Interstadial were such that average temperatures were not as warm as today, or at least as warm as during the period immediately following the Loch Lomond Stadial.

The Amulree 2 pollen diagram, for instance, exhibits an interesting pattern. Lithostratigraphy and biostratigraphy from this site indicate that soils were poorly developed during the Lateglacial Interstadial, and that shrub heath and birch woodland were unable to colonise this area during that period. During the Loch Lomond Stadial the immature soils that did exist were largely destroyed by the harsh conditions. Yet, if the radiocarbon dates can be accepted (and even if the dates are erroneous the bulk of the evidence from Scotland supports the following argument (chapter 9)) juniper heath and birch trees were able to expand dramatically in this area only a few hundred years after the close of the Stadial. Lithostratigraphy indicates that soil development and macrophytic aquatic vegetation developed rapidly at this time. The contrast between the early Flandrian pollen spectra and sediments and those of the late Lateglacial Interstadial at this site suggests that both vegetational development and soil processes were effectively restricted during the earlier period. If it is supposed that the controlling factor restricting biological developments in the late Lateglacial Interstadial is not climate but the time required for pedogenesis alone, then this same factor would surely have operated in the early Flandrian when, as a result of frost disturbance during the Loch Lomond Stadial, bare mineral soils would have characterised the slopes around Amulree. It is suggested, therefore, that the interdependent processes affecting pedogenesis and vegetational succession were hampered during the latter part of the Lateglacial Interstadial by cooling climatic conditions.

By re-examination of pollen assemblages and lithostratigraphy at Tynaspirit 2 it may be possible to delimit important climatostratigraphic horizons within the Lateglacial Interstadial. The Interstadial/Loch Lomond Stadial boundary, T2c/T2d, is defined by major changes in the <u>Betula</u> and <u>Juniperus</u> pollen frequency curves, and by a major expansion in the representation of herbaceous taxa. However, examination of the pollen spectra at this site reveals that <u>Betula</u> percentages consistently decline from a maximum throughout a large part of zone T2c, and this is paralleled by smaller reductions in <u>Juniperus</u>, and by increases in Gramineae, Cyperaceae and deteriorated pollen in advance of the biostratigraphic boundary that marks the close of the Interstadial. Further, at the T2b/T2c boundary the pollen curves for <u>Filipendula</u>, <u>Myriophyllum</u> and <u>Potamogeton</u> show marked declines. To a large extent these reductions are controlled by the relatively high influx of <u>Betula</u> and <u>Juniperus</u>, so that they may not represent real reductions in the importance of these taxa in the local flora. However, the sudden decrease in the Myriophyllum pollen curve particularly, from 14% to 4% at the T2b/T2c boundary, may indicate more than a mere statistical consequence of relative pollen influx variations. If this were so, then since Filipendula and aquatic pollen in general may indicate important thermal thresholds (Iversen, 1964) these reductions at the T2b/T2c boundary may indicate a cooling climate that resulted in temperatures below the threshold for some taxa, but not below that of juniper shrubs and birch shrubs and trees, or at least of the flowering of birch and juniper. It is possible, therefore, that the Tynaspirit 2 profile contains evidence for a deterioration of climate commencing as early as 12,395 ± 195 B.P.

Lastly in this section a few comments are necessary concerning the use of indicator species in the reconstruction of climatic conditions, particularly in relation to the reconstruction of climatic parameters for the Loch Lomond Stadial. Temperatures for the Loch Lomond Stadial in north-west England have been suggested by Walker (1966) on the basis of maximum lethal temperatures of specific plants, as determined for instance for Salix herbacea and Koenigia islandica by Dahl (1951, 1963). Another method employed by Birks (1973) involves the calculation of temperature depressions for times in the past, based on the occurrence of low-alpine vegetation at sea-level and assuming a temperature lapse-rate similar to that of today (Birks assumes a lapse rate of $0.56^{o}C$ for every 82 m).

In addition, a number of inferences have also been made from the occurrence and relative abundance (strictly, relative representation in pollen diagrams) of particular species concerning relative oceanity or continentality. Thus the local abundance of Empetrum is interpreted as indicating cool oceanic environments with a heavy cloud cover and high precipitation (Brown, 1971), and a number of inferences have been based on the real relative importance of Artemisia pollen (Walker, 1975a; Pennington, 1977) since Andersen (1961) has suggested that at the present time Artemisia appears to be chionophobous. Thus contrasts in the relative importance of Artemisia pollen between different pollen diagrams have been interpreted as indicating the local importance of a snow cover.

However, there are a number of problems involved when attempting to interpret variations in the representation of particular taxa or indeed plant community types in terms of their ecological implications. As discussed in chapter 1, Conolly (1961) has pointed out that a multi-factorial approach must be employed in deciding the limiting factors governing plant distributions in any single situation. Detailed autecological studies are required to determine the limiting effects of soil moisture, base-status, light factors, incidence of frost, maximum and minimum annual temperatures, and other factors on the present-day distribution of species. Such studies are indeed rare at the present time. The major problems associated with attempts to interpret past distributions are first, the assumption that the effects of each limiting factor were more or less identical in the past and present, and secondly, the assumption that the absence of competition by other plants does not affect basic assumptions concerning ecological controlling factors.

It is this last mentioned point that perhaps creates the most serious problems. Both Birks (1973) and Pennington (1977) have pointed out that some fossil pollen assemblages may record plant associations from the past that may have no modern counterpart. Thus, for instance, the high Empetrum pollen percentages without significant percentages of Calluna that Pennington (1975, 1977) records from the Lateglacial deposits of Cam Loch have no modern analogue. It is therefore difficult to determine the precise ecological implications of high Empetrum pollen percentages when potential competitors are absent. Conversely, it is also difficult to determine whether or not the absence or limited representation of, for instance, Empetrum, indicates climatic control or local time-lag in pedogenesis, as may have occurred between the relatively closely-located sites of Cambusbeg, Tynaspirit and Mollands.

It may be possible to develop general climatic inferences from a large body of data, such as a synthesis of data from available Lateglacial pollen profiles from the Grampian Highlands in general, and this is attempted in chapter 9. Because of the problems involved no attempt is made here to determine climatic parameters from the pollen profiles of southern Perthshire, other than those very general and imprecise inferences described above.

7. CONCLUSIONS

Evidence from lithostratigraphy, pollen assemblages, deteriorated pollen counts and radiocarbon dates from five Lateglacial pollen sites, and from Lateglacial/Flandrian transition deposits from one additional site, indicates that the Lateglacial period is broadly divisible into two climatostratigraphic units, the Lateglacial Interstadial and the Loch Lomond Stadial.

During the Lateglacial Interstadial a progressive succession of plant communities characterised southern Perthshire, from basiphilous grassland communities that colonised the area following deglaciation shortly after 13,000 B.P., to dwarf-shrub heath with birch copses in lowland sites in the latter part of the Interstadial. Juniper heath and birch trees failed to colonise the higher-lying and more exposed areas during this period. There is no evidence from any of the sites in southern Perthshire of a climatic oscillation that could be equated with the Bölling oscillation of north-west Europe. It is possible that gradual climatic deterioration commenced before 12,000 B.P. and resulted in the prevention of the development of general birch woodland in the Teith Valley, and in the further development of soils and vegetation at Amulree. This temperature decline eventually resulted in the Loch Lomond Readvance of glaciers, with limits at Callander and in upper Glen Almond, and in the break-up of the closed vegetation cover and a return to open-habitat communities and disturbed soil conditions. It is difficult to determine the chronozone boundaries of the Loch Lomond Stadial, for although litho-stratigraphic and biostratigraphic changes occurred at about 11,400 B.P., there is evidence to suggest climatic deterioration prior to that time, and the available dates for the climatic improvement that marked the close of the Loch Lomond Stadial are older than 10,500 B.P., which is significantly older than conventional dates for this transition (10,250 B.P.). Available evidence from southern Perthshire indicates the Lateglacial/Flandrian climatic transition to have been rapid, resulting in widespread development of dwarf-shrub heath, juniper heath, and then birch woodland in both lowland and upland sites.

CHAPTER 9

The Lateglacial Environment of Scotland: correlation of biostratigraphic evidence from southern Perthshire with other evidence from Scotland

1. INTRODUCTION

The last 20 years or so has witnessed a rapidly expanding number of investigations of the Lateglacial environment of Scotland. It has been apparent for some time now that the Lateglacial was a period of great environmental change in Scotland, but it is only very recently, as a result of more detailed and more varied biostratigraphic investigations, that the problems in attempting to reconstruct the complex nature of environmental change for this period have been realised. At first it was assumed that major climatic changes would be more or less synchronous across north-western Europe, and this led to a system of stratigraphic division that was designed to have a wide geographical application. The realisation of at least the possibility of non-synchronous climatic changes within north-western Europe, and the possibility that environmental changes may be more complex in one region than in another, has led to the use of local stratigraphic definitions, for local application only, with correlation not assumed but based on chronostratigraphy.

There is thus confusion in terminology and sometimes in interpretation within published biostratigraphical investigations in Britain. For instance in Scotland 58 Lateglacial pollen sites have been established since Donner (1957) first attempted to date glacial limits using palynological zonation (Fig. 35, Appendix 1). Of these 58 sites a large number have been published using the Jessen-Godwin zonation system, and in some cases assuming the Scandinavian climatostratigraphic units of Oldest Dryas, Bölling, Older Dryas, Alleröd and Younger Dryas to have direct application in Scotland. There is now a growing body of data to suggest that this assumption is incorrect, and that the use of Scandinavian terminology (which since the publication by Mangerud et al.(1974) of chronostratigraphic

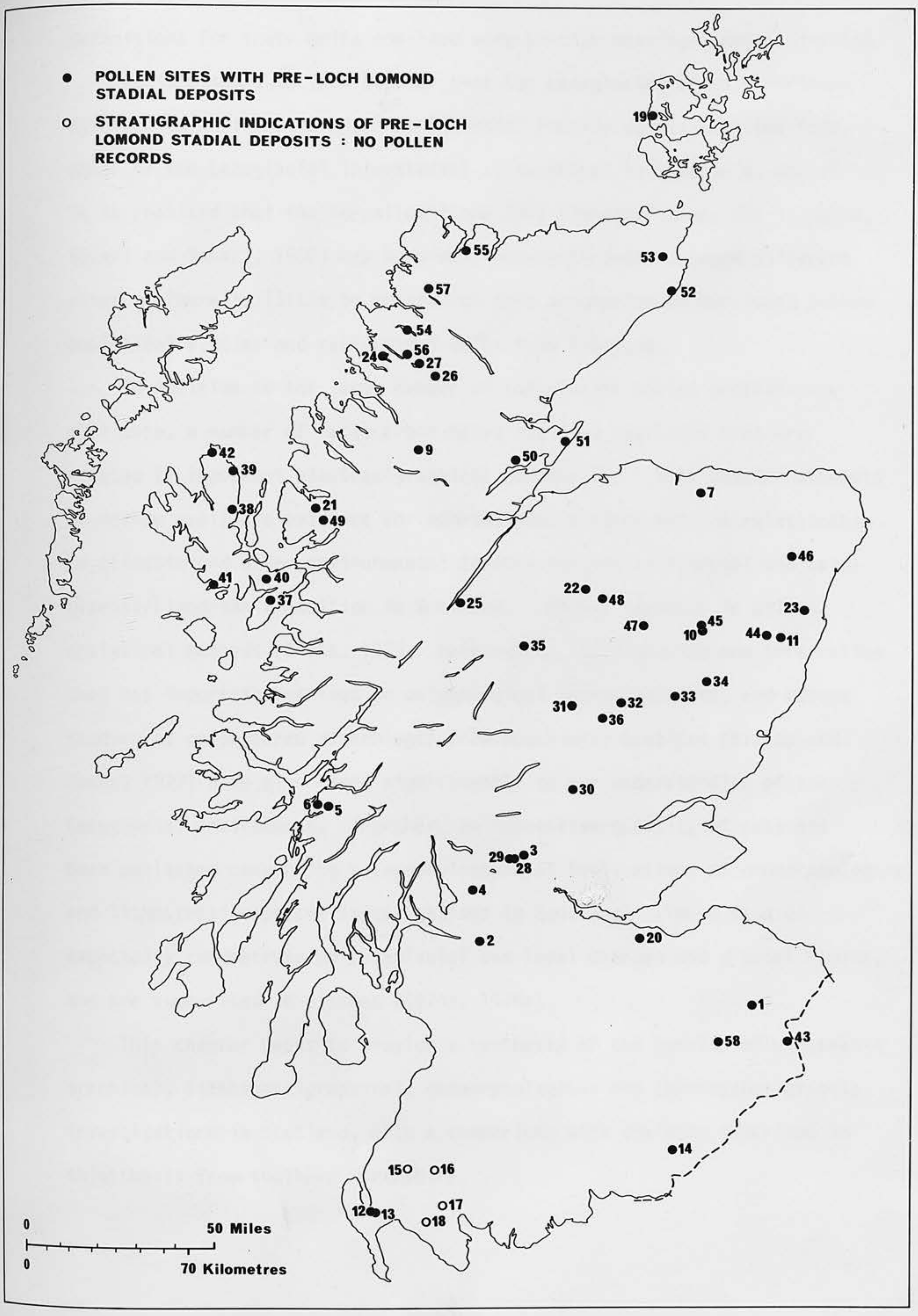


FIGURE 35 Location of sites in Scotland with pre-Loch Lomond Stadial deposits. Sources for information related to each site are listed in Appendix 1.

definitions for these units now have very precise meanings) may be invalid.

It is assumed in this chapter that the Lateglacial organic horizons referred to in the literature as "Alleröd" roughly equate with the late phase of the Lateglacial Interstadial as described in chapter 8, though it is realised that the so-called "Zone I/II boundary" (see, for instance, Vasari and Vasari, 1968) may be widely non-synchronous between different sites. There is little to contradict this assumption in published pollen analytical studies and radiocarbon dates from Scotland.

In addition to the large number of Lateglacial pollen profiles now available, a number of radiocarbon dates are also available that are related to important biostratigraphical boundaries. This chapter attempts to review available evidence for vegetational history and its relationship to climatic and other environmental factors for the Lateglacial and Lateglacial/Flandrian transition in Scotland. Recent advances in pollen analytical methods (Birks, 1973; Pennington, 1977) provide new information that has important bearings on palynological interpretations, and recent studies of coleopteran assemblages from south-west Scotland (Bishop and Coope, 1977) have also added significantly to our understanding of the Lateglacial environment. Further, an impressive quantity of data has been published concerning palaeoenvironmental implications of geomorphological and lithostratigraphical investigations in Scotland. These studies especially concentrate on Lateglacial sea-level changes and glacial limits, and are summarised in Sissons (1974a, 1976a).

This chapter seeks to provide a synthesis of the results of biostratigraphical, lithostratigraphical, geomorphological and chronostratigraphic investigations in Scotland, with a comparison with the data described in this thesis from southern Perthshire.

2. DEGLACIATION FROM THE LATE DEVENSIAN ICE-SHEET

At the height of the Late Devensian glaciation, between 17,000 and 20,000 radiocarbon years ago, most of Scotland was submerged beneath a large ice-sheet which is known to have extended as far south as Holderness in Yorkshire (Penny et al., 1969). Although a number of authors have suggested that a large part of Buchan was ice-free during this glaciation (Charlesworth, 1955; Synge, 1956; FitzPatrick, 1972), Clapperton and Sugden (1975, 1977), on the basis of the distribution of meltwater channels, fluvioglacial deposits and other considerations, have concluded that the Late Devensian ice-sheet covered the whole of Buchan.

The basal radiocarbon date from Tynaspirit 2 indicates that widespread deglaciation had taken place by about 12,750 B.P., for organic deposition had commenced in an ice-free basin close to the Scottish Highlands by this time. This date must be regarded as minimal for deglaciation in the Teith Valley, for reasons given in chapter 10.

Several other basal radiocarbon dates are available that support the concept of widespread decay in Scotland of the Late Devensian ice-sheet shortly after or about 13,000 B.P. A date of 12,940 ± 250 B.P. has been obtained from a piece of wood in a peat layer at Roberthill near Lockerbie (Bishop, 1963; Bishop and Coope, 1977). This date must also be regarded as minimal for deglaciation, for time must be allowed for the immigration and growth of trees in this vicinity. Organic silt deposits with macro-fossil plant remains from a section near Loch Droma, Ross and Cromarty, provided a date of 12,810 ± 155 B.P. (Kirk and Godwin, 1963). This date implies deglaciation at this time in an upland valley within the north-west Highlands. Close by at Cam Loch in Sutherland, Pennington (1975) has obtained a date of 12,956 ± 240 B.P. for basal organic sediments. At Drymen in Stirlingshire a date of 12,510 ± 310 B.P. has been obtained for basal clay-gyttja deposits (Vasari, 1977), and this date compares favourably with that of nearby Tynaspirit. Finally, two dates are available from sites in the Spey Valley. Basal sandy-gyttja deposits from a site in

Abernethy Forest, Inverness have been dated to 12,710 ± 270 B.P. (Vasari, 1977), and basal clay-gyttja from Loch Etteridge in upper Strathspey, Inverness, provided a date of 13,151 ± 390 B.P.

In addition to these radiocarbon dates based on terrestrial material, a number of dates are available from marine shells from the Clyde estuary, and the oldest of the dates based on inner shell layers are 12,650 ± 200, 12,610 ± 210, and 12,615 ± 230 B.P. (Bishop and Dickson, 1970; Peacock, 1971). If the radiocarbon dates from Loch Etteridge and Lockerbie are valid, and since all of these dates can be regarded as minimal for a variety of reasons discussed earlier (and in chapter 10), then there is also a strong possibility that large areas of Scotland, including Highland areas, were deglaciated by 13,000 B.P. Presumably the climatic improvement that led to this widespread ice-sheet decay must have commenced some appreciable time before then (see chapter 10).

The sites indicated on Fig. 35 contain Lateglacial Interstadial sediments and therefore prove that most of Scotland was ice-free before the Loch Lomond Readvance. There is some argument as to whether or not ice disappeared entirely from Scotland during this time. However, the recent evidence discussed in the following sections strongly suggests that the country was completely ice-free during the Interstadial.

3. <u>BIOSTRATIGRAPHIC DEVELOPMENTS IN THE LATEGLACIAL INTERSTADIAL AND THEIR ENVIRONMENTAL IMPLICATIONS</u>

Although some studies have been carried out on macrofossil plant remains and an increasing amount of research is being undertaken on faunal assemblages, present knowledge of biogeography and its relationship to climatic factors is based predominantly on palynological studies. Comparatively little is known about animal populations in general during the Lateglacial, and an understanding of Lateglacial soils and soil processes depends on inferential arguments based on palaeobotanical evidence and on a knowledge of present-day soils from arctic-alpine environments (see section 9). Reconstructions of the character of the vegetation cover at different times in the Lateglacial must take account of the problems of interpretation of palynological data, as present reconstructions rest heavily on palynological studies. A number of these problems have been outlined in chapters 1, 5 and 8. Nevertheless, despite these problems, there appears to be increasing agreement concerning the pattern of vegetational developments during the Lateglacial Interstadial.

In chapter 8 it was concluded that the Lateglacial Interstadial vegetational succession was uninterrupted (unidirectional) from soon after deglaciation (12,750 B.P.) until the major vegetational revertence phase of the Loch Lomond Stadial. Thus in each of the Lateglacial profiles from the Teith Valley there is a continuous succession from open-habitat communities, mainly species-rich grassland with a basiphilous element, through dwarf-shrub communities to a late Interstadial phase of juniper heath and birch copses. Although open-habitat vegetation prevailed throughout the Interstadial in the upland site of Amulree, there is again evidence to suggest a gradual reduction in the area of bare soils and eventual immigration of dwarf-shrub heath in the late Interstadial. In none of the profiles is there any evidence to suggest a subdivision of the Lateglacial Interstadial, and reference to a 'late' and 'early' Lateglacial Interstadial is used in an informal and imprecise way.

Similarly, on the basis of a number of pollen profiles from the Isle of Skye, Birks (1973, p.383) concluded that: "The present interpretation of the pollen stratigraphy suggests that there was a progressive unidirectional vegetation succession from low-alpine or mid-alpine communities to sub-alpine juniper scrub, presumably in response to a climatic amelioration starting at about 12,800 radiocarbon years B.P." Since the recognition of sediments of Lateglacial Interstadial age by Birks initially depended on indirect dating based on extrapolation of sedimentation rates Vasari (1977) has raised doubts as to the age of the sequence on Skye.

However, recently-obtained radiocarbon dates have confirmed the presence of Lateglacial sediments on Skye (H.J.B. Birks, pers. comm.). Further, on the basis of radiocarbon dates and four Lateglacial pollen profiles from the eastern and central Grampian Highlands Walker (1974, 1975a, 1975b, and _in_ Sissons and Walker, 1974, Lowe and Walker, 1977) agrees with Birks's concept that vegetational succession and soil development progressed without interruption from about 13,000 B.P. until the beginning of the Loch Lomond Stadial. The Lateglacial Interstadial vegetation succession from Walker's sites in the eastern Grampians (1975a) resembles that described from the sites in southern Perthshire, with a "pioneer vegetation" giving way to "a closed grassland with a locally dense shrub vegetation of willow, juniper and dwarf birch, and scattered copses of tree birch in sheltered localities on the valley floors" (p.88).

A similar Lateglacial scheme has also been proposed for sites in northern Scotland by Pennington _et al._ (1972). They identified a "pre-interstadial" and an "interstadial" which together probably equate with the Lateglacial Interstadial as defined here. Their work includes lithostratigraphical, palynological, palaeochemical, and diatom studies, and evidence could be found for only one severe environmental change within the Lateglacial, which they termed the "post-interstadial" (roughly equivalent to the Loch Lomond Stadial). "Both biological and chemical evidence indicates the continuity of soil maturation through pre-interstadial and interstadial sediments, demonstrating the absence of intense solifluction from the catchments during these periods" (Pennington _et al._, 1972, p.273).

Further, on the basis of detailed coleopteran studies from Wales and northern England Coope (1975) concluded that only one climatic oscillation was indicated for the period 13,000 to 11,000 B.P. to which he attached the informal name "Late-glacial Interstadial", a term introduced by Sissons and Walker (1974). Recent coleopteran studies from south-west Scotland have also failed to detect a distinct oscillation that could be equated with the Bölling of north-west Europe. The dominance of the coleoptera Haliplus obliquus, Haemonia appendiculata and Eubrychius velutus at Roberthill indicate that by about 13,000 B.P. average July temperatures were at least as warm as those of the present day, and evidence from Redkirk Point and Bigholm Burn, showing clearly the gradual replacement of relatively southern species by species with decidedly northern ranges, suggests a continuous climatic deterioration throughout the Lateglacial Interstadial, culminating in a "polar desert" environment which they equate with the Loch Lomond Stadial (Bishop and Coope, 1977). The insect assemblages from south-west Scotland provide further support for the recently proposed curve of average July temperature fluctuations for lowland Britain (Coope, 1975), suggesting the application of this scheme of Lateglacial environmental variation to at least lowland south-west Scotland.

Evidence for an equivalent of the Bölling oscillation has been argued for only a small number of sites in Scotland. Vasari and Vasari (1968), using the Jessen-Godwin terminology, subdivided the basal 'Zone I' at Loch of Park, Aberdeenshire, into sub-zones Ia, Ib and Ic. Sub-zone Ib, showing successive maxima of Rumex, Salix and Betula, was equated with the Bölling episode, and sub-zone Ic with an ensuing climatic deterioration. However, sub-zone Ic was delimited on the basis of one pollen spectrum only, and their interpretations must be viewed as questionable since the pollen diagram is based on relative pollen percentages. Re-investigation by Vasari (1977) at Loch of Park led to the discovery of a distinct organic layer, separated from and below the main Lateglacial Interstadial (termed 'Alleröd' by Vasari) organic deposits. Vasari argues that since pollen sub-zone Ib appeared in later (1972) cores as a layer with richer organic sediments between two layers of clay-gyttja, this provides lithostratigraphic support for the concept, previously based entirely on palynological evidence, that an early Lateglacial Interstadial climatic oscillation equivalent to the Bölling episode is evident at Loch of Park. He finds support for this concept from two more previously published sites in north-east Scotland where stratigraphical investigations have revealed basal organic horizons separated from and below the main Interstadial deposits, viz. Garral Hill near Keith (Godwin and Willis, 1959) and Loch Builg in the eastern Cairngorms (Clapperton et al., 1975). However, there are difficulties with the interpretations at both of these sites. The lower gyttja at Loch Builg has not been dated and the published radiocarbon date from the main Interstadial organic deposits is an average date for the lower half of the upper gyttja (Clapperton et al., 1975). Much more detailed analysis is required from the sediments at this site before confidence can be placed on palaeoenvironmental implications based on the stratigraphy. Also the thin lower gyttja at Garral Hill yielded a radiocarbon date (11,350 ± 300 B.P.) which is non-sequential with the date (11,880 ± 225 B.P.) from the lower horizon of the upper organic layer (Godwin and Willis, 1959). Vasari has concluded (1977) that vegetational successions from north-east Scotland are easily divisible into conventional pollen zones that can be correlated with the continental chronozone scheme, but that successions from the central and western Highlands give no indication of a climatic oscillation within the Lateglacial Interstadial. He therefore proposed that major regional contrasts in climatic conditions and climatic history existed throughout the Lateglacial Interstadial in Scotland. While this may seem a possible explanation of the apparent conflict in Scottish pollen diagrams, it requires further investigation and demonstration (see below).

A subdivision of the Lateglacial Interstadial into Bölling and Alleröd has also been strongly denied for northern England (Pennington, 1970; Pennington and Bonny, 1970) and for lowland Britain in general (Coope, 1975). However, Pennington (1975) has recently re-interpreted the profiles from Blelham Bog (north-west England) and, on the basis of changes in sediment composition indicative of slightly increased erosion of mineral soils, has identified a minor recession within Interstadial sediments at Cam Loch, north-west Scotland. A series of radiocarbon dates from Cam Loch is interpreted as indicating that the chronozone scheme proposed by Mangerud et al. (1974) for the Late Weichselian of continental north-west Europe can be applied.

Thus the recognition of an oscillation within the Lateglacial Interstadial of Scotland remains debatable. A Bölling episode does not appear to be represented in the relative pollen percentages of the great majority of Lateglacial pollen profiles from Scotland, and until more absolute pollen diagrams are available it is difficult to estimate the significance of the Cam Loch data in terms of its regional application. Further, the complex stratigraphies of Loch Builg, Garral Hill and Loch of Park also require investigation employing absolute pollen counting to establish whether or not the sedimentary and pollen assemblage changes necessarily reflect climatic changes. The detailed analyses of lithostratigraphy and deteriorated pollen analysis from the sites in southern Perthshire discussed in this thesis (chapter 6) suggest that collapse of sediments from the edge of basins and erosion of unconsolidated basin-edge deposits may have operated throughout the Lateglacial and even continued well into the Flandrian, affecting both lithostratigraphy and, as a result of the redeposition of pollen grains, affecting relative pollen percentages. Clearly absolute pollen counts are required to determine whether or not the relative pollen percentage changes at these sites are real or simply statistical accidents resulting from, for example, variation in the rate and mode of sediment accumulation, which need not relate to climatic variation.

It may be that with more precision in biostratigraphical investigations an early oscillation within the Lateglacial Interstadial will be recognised generally throughout Scotland. However, present evidence suggests first, that the oscillation must have been either of very small amplitude or of very short duration, especially when compared with the overall climatic amplitude of the Lateglacial Interstadial, and second, that such an oscillation, if it occurred, may have had a more profound effect on soils and vegetation in the north and east than elsewhere in Scotland.

As with the basal pollen spectra for profiles Tynaspirit 1, Tynaspirit 2 and Amulree (chapters 4 and 5), most Scottish Lateglacial pollen profiles accord in indicating at the base a phase of low pollen production, generally reflecting open-habitat taxa typically including Gramineae, Cyperaceae, Ranunculaceae, Chenopodiaceae, Caryophyllaceae, and _Salix_, with relatively high percentages of spores of _Lycopodium_. This is often associated with relatively high percentages of arboreal pollen, including _Pinus_, _Betula_, and sometimes _Alnus_, which suggests, because of low production of local pollen, the over-representation of grains derived by long-distance transfer (Gunson, 1975; Walker, 1975a).

The character of the landscape during the earlier phase of the Late-glacial Interstadial is reflected in the predominant minerogenic sediments, low pollen influx, the number of records of taxa indicating base-rich conditions, assemblages of benthic diatoms characteristic of base-rich and nutrient-rich waters (Haworth _in_ Pennington, 1977), the chemical composition of sediments indicating eutrophic conditions (Pennington _et al_., 1972; Pennington, 1977), and the evidence presented in this thesis for a relatively high influx of deteriorated pollen grains and spores. Thus the bulk of the evidence suggests that a characteristic open grassland vegetation prevailed, with areas of bare minerogenic soils reflected in the in-wash of nutrients and deteriorated pollen grains into lake waters.

The characteristics described above are consistent with the concept of plant colonisation of newly-deglaciated bare mineral soils at about and shortly after 13,000 B.P. However, the tundra-like vegetation and the absence of significant records of macrophytic aquatic vegetation was originally interpreted as indicating a cold 'Zone I' climatic phase. This led to difficulties in interpretation of some pollen diagrams, and several authors pointed to anomalies when attempting to impose current strati-graphical concepts and terminology. Thus Moar (1969a) interpreted

'Zone I' assemblages from south-west Scotland as "a transition representing a slow adjustment to an improving Alleröd climate" (p.462) and pointed out that conditions were not as severe during this period as during the Loch Lomond Stadial. Vasari and Vasari (1968) found difficulty in explaining the "... curious combination, in quite a marked form, of plants with northern and southern affinities ..." (p.72) in the 'Zone I' flora, and Kirk and Godwin (1963) found their basal radiocarbon date of 12,810 ± 155 B.P. (Loch Droma) quite surprising in view of current concepts of stratigraphy and glacial history, which at that time assumed the application of continental stratigraphic divisions and terminology.

Bishop and Coope (1977) have now provided evidence that indicates that by about 13,000 B.P. average July temperatures were at least as warm as today in south-west Scotland, and that soon after that in the lakes of south-west Scotland there developed a rich aquatic and semi-aquatic flora. This, to some degree, contrasts with the low organic content of sediments and with the inferred contemporary terrestrial vegetation. Studies of fossil faunal assemblages of this type are useful in adding to our understanding of the variation of terrestrial flora during the early Lateglacial Interstadial. For instance, the discovery of the weevil _Cryptorhynchidius lapathi_ in early Interstadial deposits from south-west Scotland is important since this insect drills into _Salix_ branches that are usually at least 5 cm in diameter (G.R. Coope, pers. comm.). _Salix_ bushes or trees of this type have not been indicated in any palaeobotanical records for this time, and it may be that, at least in south-west Scotland, a rich terrestrial flora, with _Salix_ bushes dominant, flourished locally in areas of faster developing soils early in the Lateglacial Interstadial.

In most of the Lateglacial pollen profiles from Scotland there is evidence for the gradual development of a closed vegetation cover and stabilisation of mineral soils throughout the Lateglacial Interstadial, and this is usually associated with a transition to organic sedimentation in lakes. The evidence from the sites in southern Perthshire and from other sites in the Grampians (Donner, 1957, 1958; Walker, 1974, 1975a) indicates that over the lower and more sheltered parts of the Grampians a closed vegetation consisting mainly of grassland, with juniper, dwarf birch, willow and occasional copses of tree birch, gradually developed. There is no macrofossil evidence for the presence of tree birch and these interpretations rest on comparatively high relative percentages of boreal birch pollen.

In Aberdeenshire an open vegetation dominated by Rumex was gradually replaced by a more closed vegetation cover with Empetrum important, and this in turn was followed by a phase of dominant juniper heath towards the close of the Interstadial, whilst tree birches "... existed as scattered copses only, without forming any real forests. On the eastern foreland of the Grampians, at Loch Kinord, some pines also occurred" (Vasari and Vasari, 1968, p.72). Vasari and Vasari include macrofossil evidence indicating a tundra-like vegetation cover with the presence of Empetrum, Betula nana, and tree birch, and a rich aquatic flora, and two needles of Pinus sylvestris have been recorded from Interstadial sediments from Loch Kinord in the Dee Valley. As in the Grampians farther to the south and west (see below) there appear to have been marked contrasts in the importance of certain taxa in different sites within north-east Scotland, for instance in Empetrum and Ericaceae, in Betula values and in the aquatic flora, that may be explained by soil differences as well as through variation in climate (Gunson, 1975).

In an attempt to reduce the problems inherent in inferring past vegetation from fossil pollen assemblages (see chapter 5, beginning of chapter 8, and Davis, 1963) Birks (1973) compared Lateglacial pollen assemblages from sites in Skye with modern pollen assemblages derived from a study of the relationships between modern pollen rain and vegetational types in Scotland. A variety of communities was represented in the late Lateglacial Interstadial vegetation, including Rhacomitrium heaths, snow-bed communities, species-rich grasslands, Empetrum heaths, juniper scrub and scattered birch copses. Birch woodland is inferred for one site, Loch Meodal, where high percentages of _Betula_ (undifferentiated) pollen and macrofossils of _Betula pubescens_ are recorded. It appears, however, that there are few modern analogues to some of the shrub-dominated (_Juniperus_ and _Betula nana_) communities recorded for the Interstadial vegetation of Skye. Birks concluded that the variety of communities recorded from the Interstadial sediments of Skye reflected an edaphic differentiation that was comparable with the complex pattern on Skye today and that the soils were far from uniform during the Lateglacial Interstadial.

Late Lateglacial Interstadial vegetation in northern Scotland appears to have been mainly characterised by an ericaceous dwarf-shrub heath (_Empetrum_ heath) and grassland cover, with a markedly variable representation of juniper (Moar, 1969a; Pennington _et al_., 1972). The new absolute pollen data from Cam Loch in Sutherland (Pennington, 1977) demonstrate that deposition rates for total pollen at this site do not exceed totals published elsewhere (Ritchie and Lichti-Federovich, 1967) for present-day dwarf-shrub tundra. In addition, deposition rates for birch suggest that at no time during the Lateglacial Interstadial did birch woodland develop, and the high percentages of _Empetrum_ without _Calluna_ in the Lateglacial pollen spectra cannot be matched with any published surface pollen spectra from Highland Britain today.

Kirk and Godwin (1963) also used comparisons with modern pollen and plant assemblages in Scandinavia to interpret Interstadial pollen spectra from Loch Droma, Ross and Cromarty. They concluded that "The plant evidence ... has to be regarded as derived from a complex of communities, ... These communities certainly seem to have included acidic _Empetrum_ heath, but there must have been also snow-patch vegetation, shallow runnels of water and marshy precincts to the open water of the lake, and stony areas probably affected by solifluction giving fresh soils of somewhat calcareous nature carrying a richly varied herbaceous plant cover. It is difficult to suppose that trees (even birch) were present except in copses" (p.247). Moss heaths dominated by the species Rhacomitrium lanuginosum were also suggested to be an important vegetation component for this period.

Available evidence from south-east Scotland also suggests that even here the vegetation of the Lateglacial Interstadial was virtually treeless in some areas, with possibly birch copses in relatively sheltered localities (such as Whitrig Bog, Berwickshire, in Mitchell, 1948). For the low-lying site of Corstorphine in western Edinburgh Newey (1970) concluded: "The herbaceous dominance characteristic of the Late-Weichselian zones appears to have been particularly marked at Corstorphine, and even during the relative warmth of Zone II, tree-pollen frequencies are very low, particularly in the middle part of the zone, where they do not exceed 15%. Most of this pollen was from Betula, and some of it was probably the result of long-distance transport" (p.1175). A species-rich grassland, with taxa indicating base-rich conditions, appears to have prevailed throughout the Lateglacial Interstadial in south-east Scotland.

A number of authors have suggested the possibility that some soil disturbance may have continued throughout the Lateglacial Interstadial, and that thus a closed vegetation cover failed to develop in much of the country. This is reflected particularly in the continued presence of taxa indicating base-rich conditions, and by the continued in-wash of a component of minerogenic sediments throughout the Interstadial (Kirk and Godwin, 1963; Moar, 1969a; Newey, 1970; Pennington et al., 1972). The evidence from Amulree in southern Perthshire and from Roineach Mhor in Glen Clova (Walker, 1975a) suggests that moss heaths and poor grassland communities were probably more characteristic of upper slopes and more exposed localities in the Grampian Mountains during the Lateglacial Interstadial. The characteristic open-habitat communities with taxa indicating bare substrates that appear to have persisted throughout the Lateglacial Interstadial at some sites indicates the absence of surface organic soil horizons. This is also reflected at Amulree and Roineach Mhor by the continuous accumulation of minerogenic sediments, and at

Amulree by the continuous high representation of physically-deteriorated pollen grains throughout this period.

Thus the evidence from Lateglacial pollen profiles from Scotland in general suggests that a complex variety of plant communities existed during the Lateglacial Interstadial, composed mainly of species-rich grassland and dwarf-shrub heath, with occasional copses of tree birch, and with extremely variable representations of Empetrum, Juniperus, and Salix. Birch woodland flourished only locally in areas of particularly favourable aspect. The northward margin of birch forest during the Lateglacial is thought to be in the vicinity of the Lake District (Pennington, 1970), while North Wales (Seddon, 1962) and Yorkshire (Bartley, 1962) are thought to have been in critical positions for birch woodland, and Northumberland (Bartley, 1966) is thought to have lacked a birch woodland cover during the Lateglacial. The immediate expansion of birch at a large number of Scottish sites during the early Flandrian suggests that some of the birch copses that developed during the Interstadial persisted as refugia during the Stadial.

Interstadial pollen assemblages, macrofossils, and lithostratigraphic data (supported by the important chemical studies of Pennington and Lishman, 1971; Pennington et al., 1972; Pennington, 1977) suggest that the intricate variation in edaphic, topographic, climatic and biotic factors that is characteristic of Scotland today must also have operated in the past to produce a complex mosaic of plant communities and extremely variable soil depths and stability. The exact climatic parameters for the Lateglacial Interstadial are difficult to determine (see this chapter, section 8), but it may be that certain local site factors, such as degree of insolation, frost incidence, wind exposure, micro-relief, drainage, chemical characteristics of soil parent materials, etc. etc., were even more critical in at least the later part of the Lateglacial Interstadial than they are today. This may have resulted not only in marked vegetational differentiation over very short distances, but also prevented the establishment of a closed vegetation cover and seriously affected soil-forming processes throughout this period (see section 9).

While maximum vegetation cover and density for the Lateglacial appears to have occurred during the latter part of the Lateglacial Interstadial, faunal remains from Redkirk Point and Bigholm Burn in south-west Scotland (Bishop and Coope, 1977) indicate that a considerable but gradual climatic deterioration actually took place between 12,000 and 11,000 B.P. The consistent increase in species with dominantly northern geographical distributions, such as *Elaphrus lapponicus*, *Amara torrida*, *Agonum consimile*, *Olophrum boreale*, suggests that towards the latter part of the Lateglacial Interstadial temperatures were significantly reduced (see section 8). It is also interesting to note that coleopteran remains also indicate the local growth of plants that are poorly, if at all, represented by Lateglacial plant fossils. Thus *Caltha palustris*, *Phillotreta flexuosa*, *Comarum palustre*, *Veronica beccabunga*, and *Epilobium* are all required food plants for beetles recorded in late Lateglacial Interstadial sediments at Redkirk Point.

4. THE GLACIAL SEQUENCE IN SCOTLAND DURING THE LATEGLACIAL

A number of readvances of ice have been proposed that would suggest an interruption to the general deglaciation from the last ice sheet to have affected Scotland. These have included Charlesworth's (1926) Lammermuir-Stranraer kame moraine, Synge's (1956, 1963) Aberdeen and Dinnet readvances, Sissons' (1967a) Aberdeen-Lammermuir Readvance, and Simpson's (1933) Perth Readvance. With the exception of the Perth Readvance all of these have recently been refuted (Sissons, 1961, 1974a; Clapperton and Sugden, 1972, 1977). Evidence for a Perth Readvance remains controversial, and though Sissons (1976a) has concluded that there is at present no firm evidence for a Perth Readvance there is the possibility that some local active movement of glacial ice may have taken place during deglaciation

(Paterson, 1974). On morphological grounds it is currently believed that no major readvance of the Late Devensian ice-sheet took place and that continuous deglaciation and probably complete disappearance of glacial ice occurred in Scotland during the Lateglacial Interstadial (Sissons, 1976a).

For how long and to what extent ice continued to exist during the Lateglacial Interstadial is uncertain. It has been suggested by Sissons that the "... widespread deglaciation that followed the Perth Readvance may well have resulted in glaciers disappearing completely from Scotland" (1967a, p.137) prior to the Loch Lomond Readvance. Until recently this view was opposed by Sugden (1970) who suggested the possibility that features in the Cairngorms correlated with the Loch Lomond Readvance could also be explained as indicating that a major ice-sheet was maintained throughout the Lateglacial over the Cairngorm Mountains and adjacent Spey valley, or that a minor fluctuation of an already existing ice-sheet could have taken place in this region during the Loch Lomond Stadial. However, the recently-obtained radiocarbon date from Loch Etteridge of 13,151 ± 390 B.P. (Sissons and Walker, 1974) discounts the first hypothesis, and recently Clapperton and Sugden (1975) have agreed that new evidence appears to suggest that a few small corrie glaciers were produced or maintained during the Loch Lomond Stadial.

Peacock (1970) has also questioned the hypothesis that ice disappeared completely from Scotland during the Lateglacial. He considered that the large volume of ice that existed in west Inverness-shire during the Loch Lomond Readvance could not have accumulated in the short time available, and he suggested that active ice existed throughout the Lateglacial in this area. However, this argument is based on the assumption that the cold climatic conditions that resulted in the Loch Lomond Readvance are delimited in age by the conventional chronostratigraphic boundaries of the Upper Dryas (Zone III). Quite apart from the fact that Sissons (1974b) has provided calculations that indicate that the relatively large ice cap that developed over the Gaick Plateau could easily have accumulated in a 500-year period, even if precipitation values were lower than those of the present day, there is also evidence to suggest that climatic deterioration commenced well before 11,000 B.P. (see section 8).

The 58 Lateglacial pollen sites shown in Fig. 35, and the associated radiocarbon dates reviewed in section 2, indicate that any ice that may have existed during the Lateglacial Interstadial was extremely limited in extent, for deglaciation was widespread in Scotland for some time prior to 13,000 B.P. The development of stable soils and closed vegetation at a number of localities in Scotland, including some upland sites within the Highlands, suggests that it is unlikely that during much of the Lateglacial Interstadial conditions remained suitable for the active accumulation of ice, and the thermal parameters based on coleopteran assemblages would certainly seem to support this (see section 8). However, there is no critical means of testing this hypothesis at present.

That ice did readvance towards the end of the Lateglacial period is now little questioned. Proof of a readvance of ice exists in the marine clays with shells that are either incorporated into or lie below terminal moraines at Loch Lomond, Menteith, Loch Creran and Loch Spelve, and which have been dated to 11,800 - 11,300 radiocarbon years B.P. (Sissons, 1967b; Peacock, 1971; Gray and Brooks, 1972). On morphological considerations a growing number of upland valleys, plateaux and corries have been mapped as having been covered by Loch Lomond Readvance ice (Sissons, 1972, 1974a, 1974b, 1977; Sissons and Grant, 1972; Thompson, 1972; Gray and Brooks, 1972). The evidence has included the mapping of the distribution of fresh hummocky moraine, fluted, terminal and lateral moraines, drift and boulder limits, contrasts with supposed (Late Devensian) ice-sheet landforms and sediments, and contrasts in periglacial features outside and within the readvance limits. Sissons (1976a) has summarised available evidence for the Loch Lomond Readvance limits, and present evidence suggests that a major ice mass developed in the western Highlands, which was surrounded by a large number of smaller glaciers.

The distribution of the Lateglacial pollen profiles (Fig. 35) indicates that the limits of the Loch Lomond Readvance must be within the Scottish Highlands, except where the glaciers spread out beyond the Highland edge in the Menteith and Loch Lomond basins. In chapter 8 it has been shown that the pollen sites Tynaspirit, Mollands and Amulree support Thompson's hypothesis that the Loch Lomond Readvance limits occur in upper Glen Almond (near Newton Bridge) and at the terminal moraine near Callander. Similarly pollen stratigraphic evidence from Loch Etteridge and Drumochter (Walker, 1975b, 1975c) supports the hypothesis that the maximal positions of the Loch Lomond Readvance are within upper Glen Truim and upper Glen Garry (Sissons, 1974b; Thompson, 1972). Drumochter occurs within hummocky moraine deposits and contains Flandrian deposits only, whereas Loch Etteridge occurs outside the proposed Loch Lomond Readvance limits and contains Lateglacial Interstadial deposits.

All the available biostratigraphic evidence for Lateglacial environmental developments is so far in agreement with the morphological delimitation of the Loch Lomond Readvance. Thus, of the 58 Lateglacial pollen profiles identified in Scotland, none occurs within the Loch Lomond Readvance limits summarised in Sissons (1976a), and a large number of test-borings within the readvance limits has failed to discover other than Flandrian or Lateglacial/Flandrian transition deposits. Thus extensive investigations have been carried out in Perthshire (chapter 2, and Donner, 1962), in Argyll (Donner, 1957; J.M. Gray and D.G. Sutherland, unpublished), in Inverness-shire and Angus (Walker, 1974, 1975c, unpublished), in Skye (Vasari and Vasari, 1968), in Sutherland (Pennington _et al._, 1972), and in the western part of the Southern Uplands (Moar, 1969a). Recently over 200 test-bores within selected areas of hummocky moraine in Rannoch Moor have also failed to discover deposits earlier than the Lateglacial/ Flandrian transition (Lowe and Walker, unpublished).

It has normally been assumed that the Loch Lomond Readvance began about 10,800 B.P. and ended about 10,300 B.P., though climatic inferences based on coleopteran assemblages from northern England and Wales have led Sissons (1976a, p.106) to suggest that "... the Loch Lomond Readvance began before, perhaps well before 10,800 B.P." The radiocarbon dates from Tynaspirit 2 and Mollands provide the only instance, so far, in the British Isles where radiocarbon dates are available from basal deposits situated immediately outside and within a Loch Lomond Readvance terminal moraine (see chapter 2). The dates from the Teith Valley would seem to date the readvance to between 11,385 ± 290 B.P. (Tynaspirit 2, Fig. 17) and 10,670 ± 85 B.P. (Mollands, Fig. 25). At Loch Etteridge the Lateglacial Interstadial/Loch Lomond Stadial boundary has been dated to 10,764 ± 120 (Sissons and Walker, 1974; Walker, 1975b), and at Cam Loch early Loch Lomond Stadial clay deposits have been dated to 10,698 ± 490 B.P. (Pennington, 1975). There appears to be some conflict between the dates at Callander and those from elsewhere, and this is especially true of the Loch Lomond Stadial/Flandrian transition dates. However, it should be pointed out that these are dates for biostratigraphic boundaries, and as such may not date with accuracy the climatostratigraphic horizons that marked the beginning and end of the climatic deterioration that caused the readvance of glaciers. Available radiocarbon dates for important biostratigraphic boundaries are reviewed and compared with the dates from southern Perthshire in chapter 10, where implications for climatic, vegetational and glacial developments are considered.

Once again!

5. BIOSTRATIGRAPHIC INVESTIGATIONS OF THE LOCH LOMOND STADIAL AND THEIR ENVIRONMENTAL IMPLICATIONS

In most Scottish Lateglacial pollen sites the Loch Lomond Stadial climatic deterioration is reflected in lower pollen concentrations and poorer pollen and spore preservation, by a reduction in the representation of shrubs and trees in pollen assemblages, and by a return to predominantly minerogenic sedimentation, often of coarse sediments, and at some sites by the virtual exclusion of aquatic pollen in pollen spectra (Walker, 1975a) or by marked changes in macrofossil records of aquatic plants (Vasari and Vasari, 1968). In a number of profiles the highest Lateglacial percentages of *Artemisia* pollen are recorded in the Loch Lomond Stadial sediments, and the associated high percentages of spores of the clubmosses *Lycopodium* and *Selaginella* and of pollen of families that include herbs indicative of open ground and disturbed soils, such as Compositae, Caryophyllaceae, Cruciferae, Chenopodiaceae and Saxifragaceae, demonstrate that over virtually the whole of Scotland there was a dramatic break-up of closed vegetation cover and consequent destruction of those surface organic soil horizons that had gradually developed during the comparatively long Lateglacial Interstadial.

An examination of available Lateglacial pollen profiles from Scotland reveals a remarkable degree of uniformity in the Stadial pollen assemblages. However, some regional and local differences are also apparent, related probably to differences in the relative amount of snow-lie. A comparison of the pollen diagrams from southern Perthshire with those published from farther north and east in the Grampian Mountains (Walker, 1974, 1975a, 1975b) reveals that particularly severe environmental conditions seem to have prevailed in the north-easterly glens. This is revealed both in the lithostratigraphy, with the accumulation of extremely coarse sediments in basins at Blackness (Glen Esk, Angus) and Roineach Mhor (Glen Clova, Angus) (Walker, 1975a), and in the biostratigraphy. Sites from the eastern glens of the Grampians suggest the widespread distribution of snowpatches, for *Salix herbacea* and other markedly chionophilous taxa are more pronounced in these sites than at sites farther west, such as Tirinie (Walker, 1974), and Amulree. This may account for the restricted records of *Artemisia* at Blackness and Roineach Mhor in comparison with other sites farther to the west and south-west in the Grampians, for *Artemisia* is known to be intolerant of snow cover today

(Andersen, 1961). However, caution is required in comparisons based on relative pollen percentages, for there are other ecological, and indeed statistical, reasons that could account for such variations (see chapter 8).

Birks (1973) concluded from a number of Lateglacial pollen profiles from Skye that there was local variation in the degree to which the vegetation was affected by the harsh climatic conditions of the Loch Lomond Stadial, for some sites (e.g. Lochan Coir a' Ghobhainn) were subjected to extensive solifluction, revealed by pollen spectra suggesting plant communities indicative of bare mineral soils and snow-bed communities, while at other sites (e.g. Loch Mealt) Betula nana heath vegetation was characteristic of the Stadial. However, differentiation in vegetation at this time is not explained as indicating variation in the severity of the climate, but as a result of edaphic differences between regions at a time when climatic conditions appear to have been equally severe at all of the sites on the island. Comparisons between fossil spectra and modern pollen spectra from Scotland suggest that the characteristic vegetation of the Stadial was "... a mosaic of low-alpine or mid-alpine chionophilous and chinophobous vegetation types that were presumably differentiated ecologically by factors of slope, aspect, and exposure" (Birks, 1973, p.347).

Pollen assemblages from Stadial deposits in Skye suggest that the vegetation communities of that time were similar to a number of present-day restricted communities in Scotland, particularly the Cryptogrammeto-Athyrietum chionophilum Association, the Saxifragetum aizoidis Association, the Polygoneto-Rhacomitretum lanuginosi Association (all described by McVean and Ratcliffe, 1962) and closely-related present-day communities from Scandinavia. This compares well with the inferred communities thought to have characterised the Loch Lomond Stadial vegetation in southern Perthshire. However, Birks (1973) has recognised a number of herbaceous pollen to species level, and also a number of fern and moss spores, which permit much more confidence in interpretations of assemblages.

Thus pollen grains of Armeria maritima, Cerastium alpinum, Plantago maritima, Polygonum viviparum, Ranunculus acris, Rumex acetosa, Saussurea alpina, Saxifraga hypnoides and Lotus corniculatus, and spores of the ferns Athyrium alpestre, Cryptogramma crispa, Dryopteris felix-mas, and Lycopodium alpinum and of the mosses Antitrichia curtipendula, Hylocomium splendens, Polytrichum alpinum and Rhacomitrium spp., have all been recognised in the Stadial spectra, some occurring in abundance. Thus much closer comparisons can be made with modern pollen assemblages and with the detailed vegetation associations described by McVean and Ratcliffe (1962) for Scotland. Birks has shown that at a number of sites the Loch Lomond Stadial vegetation was predominantly of snow-bed type, and that low-alpine and mid-alpine chionophilous vegetation persisted into the Flandrian on the island.

Palynological investigations from Loch Lomond Stadial deposits from various districts in Scotland all accord in suggesting disturbed soils, resulting from markedly increased solifluction, and base-rich conditions. Thus evidence from Corstorphine in south-east Scotland (Newey, 1970) suggests open predominantly herbaceous vegetation developed as a result of increased solifluction leading to hill wash of loosened mineral matter (see below). Thick accumulation of solifluction sediment occurred at low altitudes in south-west Scotland (Moar, 1969a), and the disturbed mineral soils are reflected in the records of pollen of Koenigia, Polytrichum alpinum and Polytrichum piliferum in Stadial deposits. Koenigia is also recorded from Stadial deposits from north-east Scotland, where disturbance of local soils must also have been widespread (Vasari and Vasari, 1968). Evidence from northern Scotland "... reinforces previous conclusions as to universal soil movements and incomplete plant cover (open communities) during the post-interstadial period ..." (Pennington et al., 1972, p.276). In some of the lochs of northern Scotland thick minerogenic sediments of Stadial age are related to increased sedimentation as a result of the presence of Loch Lomond Readvance glaciers within the catchments, while in others changes in sediment composition indicate solifluction activity.

The floristic composition of the Stadial vegetation in some respects resembled that of the colonising plant communities recorded in early Lateglacial Interstadial sediments. That many of the plants that are recorded require base-rich conditions indicates the increased erosion, resulting in mineral soils, in the catchments of a large number of basins. These include calciphilous and basiphilous species that are common in Scotland today in 'flushing' situations (McVean and Ratcliffe, 1962), shell sand and coastal limestones (Poore and McVean, 1957), base-rich rocks, especially serpentine (Proctor and Woodell, 1971; Spence, 1957), and on screes and mountain edge and ledge positions. Stadial plant communities have been likened to some present-day communities, such as the shrub-dominated communities of sub-alpine and low-alpine zones in Scandinavia (Birks, 1973), communities on the northern slopes of the Sierra de Gredos in central Spain, just below the winter snow-line (Pennington _et al_., 1972), and a variety of present-day plant associations in Scotland (see above, and chapter 8). However, Pennington (1977) draws particular attention to the very high percentages of _Artemisia_ in some Loch Lomond Stadial deposits, concluding that some Stadial pollen spectra from the northern Scottish mainland represent types of vegetation not found in northern Europe today.

Pollen assemblage evidence for climatic deterioration and soil disturbance during the Loch Lomond Stadial is supported by several other lines of evidence. Chemical analysis of Loch Lomond Stadial sediments from northern Scotland indicates deposition of mineral matter from weathered (Lateglacial Interstadial) as well as unweathered material derived from glacial erosion of local soils (Pennington _et al_., 1972; Pennington, 1977). There appears to be no evidence from the palaeochemical data of erosion of unleached drift or rock, but Pennington _et al_. (1972, p.226) suggest that "post-interstadial sediment originated in interstadial soils, sludged into the basin during a period of cold climate." This can be compared with evidence from south-east Scotland (Newey, 1970) where the abundant derived spores of Carboniferous type indicate that soil parent materials were also affected by solifluction processes at this time.

Diatom assemblages have also supported interpretations of Stadial environmental conditions based on pollen assemblages. Thus Vasari and Vasari (1968) provide detailed evidence for changing base-status and consequently of aquatic flora which is partly based on diatom assemblage evidence (Alhonen, 1968), and which suggests that the changing conditions of the lakes resulted from solifluction "... which brought the leached surface layers of the surrounding ground, covered formerly by heath-like vegetation, into the loch thus causing a falling of its pH" (Vasari and Vasari, 1968, p.75). More detailed diatom analyses reported in Pennington _et al_. (1972) and by E.Y. Haworth _in_ Pennington (1977) support pollen and chemical evidence for renewed soil disturbance. This is especially reflected in the increased representations of taxa that live subaerially on soils, wet rocks and among mosses, such as _Navicula fracta_ and _Pinnularia suchlandtii_.

In the present work the increased erosion of soils during the Loch Lomond Stadial is reflected in the markedly increased percentages of physically-deteriorated pollen and spores in Stadial sediments (chapters 6 and 8). Increased relative percentages of corroded pollen have been attributed to the in-wash of Lateglacial Interstadial soils.

There is little faunal evidence from Scotland for environmental conditions during the period from 11,000 to 10,000 B.P. However, a species-poor fauna has been recorded from Stadial sediments from Bigholm Burn in south-west Scotland (Bishop and Coope, 1977), and rigorous climatic conditions are indicated by the dominance in the coleopteran assemblages of the low temperature stenothermic species _Olophrum boreale_. Faunal assemblages collected by Bennie (1891, 1894) are not particularly helpful as precise palaeoenvironmental indicators as subjective selection of species, according to conspicuous appearance, has biased the samples (Coope, 1968; Newey, 1970).

In almost all Lateglacial basin deposits in Scotland the opening up of the vegetation and severe climatic conditions are reflected in litho-stratigraphic criteria by the predominantly minerogenic sedimentation during the Loch Lomond Stadial. In some sites, particularly in south-east Scotland, the eastern glens of the Grampian Mountains, and in northern Scotland, coarse sediments were produced, suggesting active solifluction and/or increased effectiveness of fluvial erosion processes on surrounding slopes. In other sites, such as those described in this thesis from southern Perthshire, fine clays and silts characterise the Stadial sediments. Whether this represents differences in the effectiveness of frost disturbance in different areas or local variations in sediment transport or depositional processes is at present unclear.

In addition to the minerogenic lake sediments dated to the Loch Lomond Stadial, there are reports of direct evidence of periglaciation during this time. Thus a layer of solifluction gravel at Bigholm Burn, south-west Scotland, has been dated to between about 11,500 and 9,500 B.P. (Bishop and Coope, 1977). Solifluction is also indicated by Lateglacial Interstadial deposits that have been buried by layers of solifluction debris, at Tarves, Aberdeenshire (Gunson, 1975), Inverbervie, Kincardinshire (Donner, 1961) and Garral Hill, Keith (Donner, 1957), in north-east Scotland. Three frost wedges have been reported from localities just inside the limits of the Loch Lomond Readvance, one in north-west Scotland (Sissons, 1977) and two on Mull (J.S. Bibby, unpublished; J.M. Gray, pers. comm.), and these suggest that retreat of the Loch Lomond Readvance glaciers in some localities may have commenced prior to the major climatic improvement of the Lateglacial/Flandrian transition (see section 8 and chapter 10). Rose (1975) has reported two deep frost wedges in beach gravels at Old Kilpatrick in the Firth of Clyde, and has concluded that these were formed during the Loch Lomond Stadial. Finally, Sissons (1972, 1974a, 1974b, 1976a) has suggested that major solifluction lobes in the Highlands were formed during the Loch Lomond Readvance, and has used the distribution of such lobes to delimit the Loch Lomond Readvance maximum.

There is thus much evidence to support conclusions based on pollen assemblages that during the Loch Lomond Stadial closed vegetation communities were severely disturbed and Lateglacial Interstadial soils were subjected to increased erosion and in places cryoturbation. Solifluction mass movements (gelifluction) occurred in some locations, and there is evidence to suggest production of ground ice and erosion of soil parent materials as well as upper soil organic layers, even at sea-level.

6. THE LOCH LOMOND STADIAL/FLANDRIAN TRANSITION

It is generally agreed that the transition to warmer and more stable conditions at the close of the Loch Lomond Stadial occurred rapidly. This is reflected in a large number of sites by an abrupt change from minerogenic to organic sedimentation, even where coarse minerogenic sediments were deposited during the Stadial. Thus at both sites in the eastern Grampians where coarse Stadial sediments occur (Blackness and Roineach Mhor (Walker, 1975a)) a sharply defined lithostratigraphic horizon occurs reflecting "... the sudden cessation of minerogenic inwash, the stabilisation of the vegetation pattern and the development of the basin ecosystems" (p.86). As in the sites from southern Perthshire, a dominant _Empetrum_ and _Juniperus_ heath became quickly established throughout the Grampian Mountains following the close of the Loch Lomond Stadial (Donner, 1957, 1958, 1962; Walker, 1974, 1975a, 1975b). Other similarities between these sites and those described in this thesis are the marked expansions of aquatic flora, especially _Myriophyllum_ cf. _alterniflorum_ and _Potamogeton_, and of the relatively thermophilous terrestrial Filipendula cf. ulmaria, which suggest significant improvement in climatic conditions.

Empetrum and Juniperus heaths expanded quickly over virtually the whole of the mainland of Scotland and in the Isles, and birch woodland spread to most parts of the country less than 1,000 years after the beginning of the Flandrian (see chapter 12). Successive vegetational changes from open species-rich grasslands, to dwarf-shrub heaths (dominated by Empetrum), to Juniperus scrub, and then to birch woodland is a repeated Loch Lomond Stadial/Flandrian transition pattern recorded in north-east Scotland (Vasari and Vasari, 1968), south-west Scotland (Moar, 1969a), northern Scotland (Pennington, et al., 1972), and the Isle of Skye (Vasari and Vasari, 1968; Birks, 1973) as well as in the Grampian Mountains.

The expansion of aquatic flora that is a marked feature of the majority of pollen profiles from Scotland that include Loch Lomond Stadial/Flandrian transition deposits has been related to a thermal improvement of climate (see above), but the dramatic increase in aquatic pollen percentages for this time has also been interpreted as indicating an extremely rich aquatic flora that probably reflects eutrophication of lake waters. Detailed analyses from Skye (Birks, 1973) indicate that members of the aquatic macrophytes at this time were Littorella uniflora, Ranunculus trichophyllus, Nitella, Isoetes lacustris, Pediastrum and Botryococcus. From sites in Aberdeenshire Vasari and Vasari (1968) have recovered macrofossils of Potamogeton praelongus, Ceratophyllum, Chara, Nitella, Najas flexilis, Isoetes echinospora and I. lacustris. Both Birks and Vasari and Vasari conclude that the degree of eutrophication that these assemblages imply was probably a result of the recycling and inwash of minerogenic sediments during the Loch Lomond Stadial.

A further factor may also have been important. The marked expansion of aquatic flora may have been partly related to increased depths of light penetrating the waters in the lochs and small basins. During the Loch Lomond Stadial increased loads of clay and silt would have resulted in cloudy water, and since the productivity of submerged and partly submerged aquatic vegetation is dependent on the amount of light penetrating the water then productivity is likely to have been markedly checked until reduced rates of erosion resulted in clearer waters in the early Flandrian.

The sharp transition from the severe environmental conditions of the Loch Lomond Stadial to the more stable and warmer conditions of the early Flandrian is also reflected in the dramatic decrease (to the lowest values in the diagrams) in percentages of deteriorated pollen grains and spores in each of the five pollen profiles and Lateglacial/Flandrian transition profiles from southern Perthshire for which this type of data is available (see chapter 6 and Fig. 33). Further, rapid environmental changes are inferred from chemical evidence of changes in sediment composition, for in a number of sites in northern Scotland carbon content increases markedly to values higher than those reached at any horizon in the Lateglacial Interstadial during the "transition" phase (Pennington et al., 1972; Pennington, 1977).

Coleopteran evidence from early Flandrian deposits at Brighouse Bay in south-west Scotland supports evidence reported earlier from the English Midlands (Ashworth, 1973; Osborne, 1974) that the climatic transition at the beginning of the Flandrian occurred with remarkable rapidity, possibly in a period of less than 500 years, resulting in a change from a climate of arctic severity to a climate similar to that of south-west Scotland today (Bishop and Coope, 1977). A dated horizon from Brighouse Bay of 9,640 ± 180 B.P. reveals that by then all northern insect species had disappeared and in their place a rich temperate assemblage had become established.

It is difficult to determine precisely the age of the climatic improvement that led to the retreat of the Loch Lomond Readvance glaciers, the cessation of minerogenic soil inwash, and the development of closed vegetation over Scotland. The unexpected results of radiocarbon determinations of samples from southern Perthshire has already been described (Chapter 8), and radiocarbon dates presently available for the biostratigraphic Stadial/Flandrian boundary are quite widely variant. These are listed in Table 8 and discussed in more detail in chapter 10. It appears that the environmental consequences of the climatic improvement, such as glacial retreat, immigration of shrub heath vegetation, and cessation of minerogenic inwash, may have been noticeably time-transgressive in Scotland.

Though the climatic transition at the end of the Loch Lomond Stadial appears to have been very rapid, there is evidence for some time-lag in the development of landscape stability at a number of sites. Thus minerogenic sedimentation continued into the early part of the Flandrian at sites in south-west Scotland (Moar, 1969a) and in Skye (Vasari and Vasari, 1968; Birks, 1973; Vasari, 1977). The continued representation of species-rich grassland communities in parts of the Teith Valley while other parts supported dwarf-shrub and juniper heaths is reflected in the detailed pollen assemblages of the Mollands pollen diagram described in chapter 8. Similarly, Birks (1973) has interpreted pollen assemblages from transitional deposits in Skye as partly representing associations similar to the Dwarf Herb _nodum_ and 'tall herb' communities described by McVean and Ratcliffe (1962). In sites that were ice-covered during the Loch Lomond Stadial this time-lag would probably have been much longer and records of grassland and moss heath communities are more obvious in the early Flandrian deposits in such sites. This is especially reflected in the abundant remains of _Rhacomitrium lanuginosum_ washed in with Loch Lomond Stadial/Flandrian deposits at Nick of Curleywee in the Merrick-Kells hills in Kirkudbright (Moar, 1969a), and at Kingshouse in the western part of Rannoch Moor (Lowe and Walker, in press).

In chapter 8 (section 6) it was argued that because of the contrasts in vegetational developments in the early Flandrian and late Lateglacial Interstadial periods climatic conditions, at least in the later part of the Lateglacial Interstadial, may have prevented further development of soils and the further expansion of juniper heath and birch woodland. The evidence reviewed in this chapter from Scotland as a whole adds strength to this argument. It has been shown that in a number of sites in Scotland minerogenic inwash continued throughout the Lateglacial Interstadial and yet at these same sites (Amulree, Roineach Mhor, Lochan Cill Chriosd) minerogenic sedimentation ceased abruptly at the Loch Lomond Stadial/ Flandrian transition. During the Lateglacial Interstadial, a period of up to 2000 years, pedogenesis continued without major interruptions in most parts of Scotland, but during the Loch Lomond Stadial cryoturbation disturbed the normal soil-forming processes destroying soil horizons that may have developed during the Interstadial.

Thus the substrates on which vegetation communities had to become established were probably soil parent materials of unweathered or only slightly weathered mineral particles, often of coarse texture and without any significant content of organic matter. Yet within a few hundred years following the close of the Stadial (see Chapter 10) vegetation succession had progressed beyond the plant communities recorded for the Interstadial, organic carbon content increased to levels much higher than those recorded during the Lateglacial Interstadial, deteriorated pollen percentages are the lowest for the whole of the Lateglacial profiles, a strongly thermophilous element is recorded in both terrestrial and aquatic flora that are much less prominent in Interstadial assemblages, and juniper heath and birch woodland especially were able to immigrate into areas that they did not colonise at any stage in the Lateglacial Interstadial. Taking the evidence from Scotland as a whole it would seem that the rapid environmental changes that took place during the relatively short Loch Lomond Stadial/ Flandrian transition have major implications for the late phase of the Lateglacial Interstadial (see chapter 8, section 2), and it is suggested that climatic deterioration had already progressed to such a level in the Interstadial that important limiting thresholds for a number of plants had been crossed some time before 11,000 B.P.

7. CLIMATIC DEVELOPMENTS DURING THE LATEGLACIAL AND LATEGLACIAL/FLANDRIAN TRANSITION: CLIMATIC PARAMETERS

Plants are exceedingly slow to react to climatic alterations, especially in the context of the comparatively rapid climatic changes that characterise the Quaternary period (Coope, 1970, 1975), and calculations of climatic parameters require support from other lines of evidence. Lateglacial climatic parameters can be better inferred from fossil coleopteran assemblages, the use of calculated firnline altitudes, and from inferences based on fossil periglacial features.

On the basis of coleopteran studies from the Midlands of England and north Wales (Coope et al., 1971; Coope, 1975) a temperature curve has been constructed that suggests that at around 13,000 B.P. mean July temperature was about 17°C, and following this mean July temperature declined sharply to about 13-14°C at about 12,000-12,500 B.P. A temperature of 9-10°C (mean July) is suggested for the Stadial, and a rapid increase to about 17°C (mean July) is proposed for the Stadial/Flandrian transition. A newly-constructed curve for south-west Scotland based on coleopteran assemblages suggests the same overall pattern of mean July temperature variation, with slightly different values (Bishop and Coope, 1977). Thus at about 13,000 radiocarbon years ago the mean July temperature was about 15°C, which is not much different from that of south-west Scotland today. A sharp decline in mean July temperature, to about 12-13°C, is inferred for some time between 12,000 and 12,500 B.P., and a gradual climatic deterioration then followed during the later part of the Lateglacial Interstadial, which culminated in the Loch Lomond Stadial with values of 8-9°C for mean July temperature. The evidence from Brighouse Bay (see section 6 above) indicates that climatic improvement at the end of the Loch Lomond Stadial was rapid resulting in a mean July temperature of at least 15°C, and Bishop and Coope conclude that at the beginning of the Flandrian the climate of south-west Scotland was at least as warm, and perhaps even rather warmer, than that of the present day in that area.

A number of climatic inferences for the Loch Lomond Stadial period have recently been based on calculated firnline altitudes. On the basis of detailed mapping of former glacial limits and estimated former precipitation values Sissons (1974b) has inferred that the average June-September temperatures for the Gaick Plateau in the central Grampian Mountains at the time of the Loch Lomond Readvance were about 1.5°C at the firn line, and this in turn suggests an equivalent (contemporary) sea-level temperature of 6.3°C for the July-September average, or ca. 7.6°C for mean July temperature. Taking latitudinal difference into consideration this estimate compares well with the inferred July temperatures for the Loch Lomond Stadial in south-west Scotland based on coleoptera.

Using a similar procedure a firnline altitude has been calculated for the Loch Lomond Readvance ice cap that developed on Mull (J.M. Gray, unpublished). A mean July temperature of 5°C has been calculated for the Loch Lomond Stadial at sea-level in Mull. The firnline for this ice cap has been calculated as about 250 m above present sea-level, whereas the firnline for the Gaick ice cap was at an elevation of 790 m. Clearly a steep west-east rise in the firnline across Scotland occurred in the Loch Lomond Stadial, probably related to variation in precipitation values. Recently Sissons and Sutherland (1976) have computed a regression surface for glacier firnlines in the south-east Grampians, and from this they have inferred a mean July sea-level temperature of about 6°C, a greater cloud cover, at least in summer, than at present, and similar precipitation values to those of the present day, though precipitation was probably different in its spatial distribution.

Ice wedge casts at Kilpatrick in the Firth of Clyde are thought to have developed in beach gravels during the Loch Lomond Readvance, and from this a mean annual temperature, employing criteria established by Péwé (1966), of less than -6°C has been inferred (Rose, 1975). Similarly, the frost wedges present in sands and gravels just inside the maximal extent of the Loch Lomond Readvance on Mull and in Wester Ross (see section

5, this chapter) imply a mean annual temperature at sea-level at least as low as -6^{o}C, and perhaps as low as -8^{o}C, according to Péwé's criteria. If these inferences are correct, then they indicate exceedingly low winter temperatures at sea-level in Scotland during the Loch Lomond Stadial. However, Sissons (1974a, 1976a) has advised caution concerning the application of Péwé's thermal limits (based on present-day features in Alaska) to fossil features in Scotland.

Peacock et al. (1977) have used marine shell and microfaunal evidence to infer climatic parameters for part of the Lateglacial. They conclude that the climate of Scotland was probably more severe in the early phase of the Lateglacial Interstadial than at present. This, therefore, is in conflict with the climatic inferences based on coleoptera. However, as Ruddiman and McIntyre (1973) point out, marine faunal assemblages are often of little value for calculating air temperatures, for cold assemblages often result from the influx of low temperature water from melting ice sheets and glaciers, while contemporary land surface or air temperatures may be comparatively warm. Thus the use of marine mollusc assemblages to calculate mean July air temperatures is exceedingly questionable.

It is difficult to establish thermal parameters from palaeobotanical data alone, for there is the possibility that the vegetation cover at any particular time is not controlled primarily by climatic factors but by the time-lag in pedogenesis, by migration rates of individual species, or by local site factors. Thus in view of these possibilities, and of the problems outlined in chapter 1 and in section 6 of chapter 8, and also because of the possibility of misinterpretations for which evidence has been provided by Coope (1970, 1975) and Coope and Brophy (1972), it is felt that calculation of temperature depressions based on theoretical lapse rates for periods when low-alpine vegetation existed at sea-level must be regarded as questionable (Birks, 1973). Similarly the temperature inferences based on detailed botanical evidence by Walker (1966), Pennington (1970), and Conolly and Dahl (1970) may be far from precise.

It has been suggested by Iversen (1954) that the presence of Betula pubescens in a local flora implies a mean July temperature of at least 12°C. The macrofossil records of Betula pubescens from Skye (Birks, 1973) and the development of tree birch copses throughout Scotland during the Lateglacial Interstadial indicate that temperatures of about or in excess of 12°C were maintained long enough to permit the general immigration of this tree. Consistent records of Littorella uniflora (Shore-weed) pollen from the latter part of the Lateglacial Interstadial in Skye has also been interpreted as indicating mean July temperatures of 14°C or more for this time (Birks, 1973). Bishop and Coope's (1977) average July temperature curve for the Lateglacial suggests about 12°C for the latter part of the Interstadial. Thus the estimates for Skye based on the presence of Shore-weed are a little higher than, and those based on the presence of tree birch are in agreement with, values based on coleopteran assemblages.

8. CLIMATIC INFERENCES FOR THE LATEGLACIAL PERIOD IN SOUTHERN PERTHSHIRE

The basal radiocarbon date from Tynaspirit 2 (Fig. 17) suggests that parts of southern Perthshire had been deglaciated for some appreciable time prior to 12,750 B.P., for landscape stability subsequent to deglaciation is indicated by the predominant organic sediments and by the development of a dwarf-shrub heath by that date. There is no evidence from southern Perthshire for thermal parameters for that time, but it would seem reasonable to infer that temperatures were not greatly dissimilar to those calculated for south-west Scotland by Bishop and Coope (section 7). Thus average July temperatures were probably about 15°C, at least for the lower-lying parts of the region (as around the lower Teith Valley) by as early as 13,000 B.P., and it is possible that the Tynaspirit 2 kettle hole may have been deglaciated by that date. Since no Lateglacial organic deposits are available for Cambusbeg and Amulree it is impossible at present to estimate the date of deglaciation of these kettle holes.

According to Bishop and Coope temperatures had decreased sharply by about 12,000 B.P. to mean July values of 12^{o}-$13^{o}C$ in lowland south-west Scotland. It has been argued (chapter 8) from the representation of Betula and Juniperus in the pollen diagrams from southern Perthshire first, that temperatures are unlikely to have been in excess of $12^{o}C$ in the Teith Valley around Callander for the later part of the Lateglacial Interstadial; secondly, that the critical threshold for the growth of birch woodland (mean July temperature of $12^{o}C$) was probably limited to an elevation between that of Callander and of Amulree during the late Lateglacial Interstadial; and thirdly, that climatic deterioration could be detected in the pollen diagrams prior to the date of the biostratigraphic boundary for the Lateglacial Interstadial/Loch Lomond Stadial transition, dated at Tynaspirit 2 to 11,385 ± 290 B.P.

There are few radiocarbon dates available from south-west Scotland, and Bishop and Coope's mean July temperature curve requires critical testing in the future; as yet it rests upon a series of widely-separated partial Lateglacial faunal records. Further, it is impossible to interpret the pollen profiles from southern Perthshire in terms of inferred temperature values, apart from the crude inferences discussed above. Also, absolute pollen counts and additional radiocarbon dates are required in order to determine more accurately the horizon in the Tynaspirit 2 diagram indicating climatic deterioration during the Lateglacial Interstadial. Nevertheless there is nothing in the coleopteran records from south-west Scotland or the pollen profiles from southern Perthshire to contradict the proposal by Bishop and Coope (1977) of a two-fold subdivision of the Lateglacial Interstadial, a scheme supported by evidence from northern England and Wales (Coope, 1975). Thus it is here tentatively proposed that the Lateglacial Interstadial was characterised by two broad climatic divisions; an early phase where temperatures were, at least in the earliest stages, at least as warm as those of today, and during which widespread deglaciation occurred; and a second late Lateglacial Interstadial phase when climate had deteriorated to such an extent that this prevented the establishment of tree birch and juniper heath in large parts of southern Perthshire. Average temperatures during the late Interstadial phase may have been below the critical threshold of a number of plants, including aquatic macrophytes (see chapter 8).

It is therefore suggested that temperatures at low elevations in southern Perthshire during the period, 12,000 - 11,400 B.P. (and possibly as late as 11,100 B.P.) were of the order of $12^{o}C$ (mean July). If this conclusion is correct, then using a lapse rate of $0.68^{o}C$ for every 100 m (derived from Manley's (1952) rate of $1^{o}F$ for every 270 feet), this would imply a mean July temperature at Amulree of approximately $10^{o}C$ (the altitudinal difference between Callander and Amulree is 270 m). Because of the steeper slopes around the Amulree site, the greater degree of shading, probable higher incidence of colder winds and longer duration of snow-lie, and probable greater amount of cloud cover, the temperature difference between Callander and the upper Glen Almond-Corrymuckloch district may have been somewhat greater than this calculated figure. Thus during the late Lateglacial Interstadial phase critical thresholds for the immigration of a large number of plant taxa may have been at a lower elevation than the Amulree site which may therefore account for the contrasts in the litho-stratigraphy and biostratigraphy for the Lateglacial between the sites of Amulree and Tynaspirit. Furthermore, climatic deterioration during the Lateglacial Interstadial would have had effects on local vegetation earlier in upper Glen Almond than in the lower Teith Valley, and the steeper slopes around Amulree would have been an added barrier to the development of stable soils and a closed vegetation cover.

Using Sissons and Sutherland's (1976) inferred temperature values based on a computed regression surface for glacier firnlines in the south-east Grampians, it would appear that a mean July sea-level temperature of about $6^{o}C$ was experienced in the south-east Grampians during the Loch

Lomond Stadial. Thus during the colder stages of this period temperatures around Callander may have been of the order of 5.5^{o}C (mean July) and in the upper Glen Almond-Corrymuckloch region mean July temperatures may have been as low as 3.0^{o}-3.5^{o}C. Thus winter temperatures may have been exceedingly low at this time, especially around the site of Amulree. However, comparisons of the Stadial plant associations of Amulree and of lower areas such as the Teith Valley are not straightforward, for a decisive factor in winter would be the relative duration and amount of snow cover, protecting the ground surface (and plants) from the extremes of winter cold.

Bishop and Coope (1977) have suggested that a dramatic rise in temperature occurred at about 10,000 B.P., with the result that temperatures were as warm as today by about that time, or very soon after. The evidence from sites in southern Perthshire suggests that marked climatic improvement may have begun much earlier than this, possibly as early as 10,700 B.P. The validity of the radiocarbon dates from southern Perthshire must be further tested, but no critical dates are available from the sites studied by Bishop and Coope to verify the timing of the climatic improvement that marked the end of the Loch Lomond Stadial in south-west Scotland.

9. THE LATEGLACIAL SOILS OF SOUTHERN PERTHSHIRE

Lateglacial pollen records and macrofossil studies of Lateglacial assemblages indicate that the Lateglacial land surface of Scotland was characterised by a vegetation that physiognomically resembled present-day arctic tundra vegetation. It can therefore be inferred that the soils associated with the Lateglacial plant communities must also have resembled, in general terms, the soils to be found in present-day arctic environments, though this inference requires a certain amount of caution (see below). Thus some discussion of present-day 'Tundra soil' is required prior to any attempt to establish the likely character of the Lateglacial soils of southern Perthshire.

Though 'Tundra soil' has been classed in world classifications as a Great Soil Group the term refers mainly to hydromorphic soils and thus does not bear the same connotations as other Great Soil Groups (Charlier, 1969). In fact, soils developing in freely-draining situations are uncommon in arctic areas, but though they account for an extremely small area they are nevertheless a very important component of 'Tundra soil'.

The dominant factors affecting the development of soils in the arctic are low temperatures and, in most places, the presence of an impermeable perennially-frozen substratum, together with a variable cover of herbaceous or dwarf shrub or bryophytic vegetation. Frost-disturbance disrupts normal soil-forming processes, preventing the formation of soil horizons (Raup, 1951; Sigafoos, 1952). The presence of a perennially-frozen substratum means that over large areas soils are usually or always saturated, and in the absence of any deep root system (which is also partly a result of frost activity) organic matter accumulates only at the soil surface in the poorly drained soils (Everett, 1971; Rieger, 1974).

These features are so widespread in arctic areas that it is tempting to imagine soils of arctic areas as being rather monotonous. In some respects that is true, for although it is difficult to classify soils of arctic areas, it has been found that soil conditions often vary more abruptly yet repetitively in arctic areas than in temperate areas (Drew and Tedrow, 1962). Soil conditions vary according to relative saturation and the relative degree of frost disturbance, and a basic two-fold sub-division of arctic soils has been found to be convenient: those that are relatively undisturbed by frost and those that are severely frost-disturbed. Further subdivision can then be made according to the degree of saturation (Tedrow, 1962; James, 1970). On the best-drained slopes that also experience little frost-disturbance weakly-defined soil horizons have been discovered.

Horizonation in soils of arctic areas thus occurs only extremely locally. In those areas of the northern hemisphere so far studied in detail soils with horizons occur most often on the crests of ridges, escarpment edges, the edges of river terraces, and on old beach ridges, especially where coarse sand and gravel predominate in the substratum (Hill and Tedrow, 1961). They also occur on the upper portions of stabilised sand dunes (Tedrow and Cantlon, 1958). Thaw occurs earlier on such sites, is deeper and lasts longer in the summer months, and thus soil temperatures and biological activity are higher than on adjacent poorly-drained areas (Drew et al., 1958).

In the best-drained areas of arctic Alaska and Canada an Arctic Brown Soil (Tedrow and Hill, 1955) has been recognised. A weak podsolic process characterises this soil, though sometimes this can only be detected by chemical and mineralogical techniques. Because of low temperatures, weathering and podsolic processes are extremely slow. For instance, four Arctic Brown soil profiles have been studied in Alaska, and though chemical weathering was found to be in operation, the results of laboratory measurements revealed this to be of a very low order (Hill and Tedrow, 1961). Evidence of podsolisation has also been found in the Arctic Brown soils of the Canadian Arctic Barren Lands, where an iron pan was discovered in one profile examined (James, 1970). Weak podsolisation in soils of the Cambrian Lake region, Quebec, has been found to be primarily dependent on parent material, where the important factor is the relative quantity of available ferro-magnesian minerals (Moore, 1974).

In James' (1970) study of soils in the Canadian Arctic no essential differences were found between soils that have been developing for more than 4,000 years and soils which have had considerably less time to develop. It is not primarily the time factor that is important but local site conditions, including parent material, slope, drainage, periglacial processes and vegetation. In making inferences concerning Lateglacial soils in southern Perthshire from studies of soils in present-day arctic environments, it has been noted that James has found evidence for weak podsolisation processes in a permafrost area with a seasonal thaw of between 25 cm and 1.8 m, and with an average July and August temperature of below 10^{o}C.

Thus, in summary, soils of arctic areas are extremely poorly developed, as a result of frost activity, particularly where the active layer is thin, and also as a result of saturation, which can be almost a constant in depressions and on slopes of low angle. Histosols (U.S.D.A. Soil Survey Staff, 1960) can account for about 75% of the land surface in arctic and sub-arctic areas (Everett, 1971). Because of their comparative rarity it is only very recently that the process of podsolisation and the importance of Arctic Brown soils have been recognised in arctic areas, but their recognition has important implications for our understanding of the Lateglacial land surface of Scotland.

It has already been inferred (see above) that during much of the Lateglacial Interstadial mean July temperatures for southern Perthshire were probably in excess of 12^{o}C, and in the earlier part of the Interstadial temperatures were as high as those of today. Further, it is currently supposed that Scotland was completely deglaciated during the Interstadial (Sissons, 1976a), and pollen evidence provided in this thesis suggests a degree of soil stability, at least in lower-lying areas (in the main valleys) during much of this time. It therefore seems unlikely that frost disturbance was a major environmental factor during the Lateglacial Interstadial in large parts of southern Perthshire, though it would have continued to seriously affect vegetation and soil-forming processes in upland areas such as around Amulree, and the steeper and higher slopes of the Grampians generally. Thus, in comparison with present-day arctic areas, podsolisation processes would probably have been stronger in southern Perthshire during the Lateglacial Interstadial due to higher average annual temperatures and an absence of perennially-frozen ground. In making an analogy between soils of present-day arctic areas and those of Lateglacial Scotland more importance can probably be attached to Arctic Brown soils in the latter, though in the limited time available horizons would probably have been extremely weakly developed.

A number of factors can be taken into consideration in estimating the likely importance of Arctic Brown soils during the Interstadial in southern Perthshire. Much of the terrain in the valley bottoms is of a hummocky or moundy nature, and slopes there, as well as on the main valley sides, would have provided suitable freely-draining sites in the absence of an impermeable frozen substratum. Much of the deposits of the floors of the main valleys (for instance the Teith Valley - see Fig. 6) are composed of sands and gravels, in the form of kames, eskers, kame terraces and fluvial terraces. Hill and Tedrow (1961) point out that soil horizons are particularly well developed on coarse sands and gravels in arctic environments. The local drifts and rock types are not notably rich in ferro-magnesians, the latter being composed predominantly of schistose grits and quartzose mica-schist north-west of the Highland Boundary Fault, and of sandstones south-east of the fault. Further, the pollen diagrams from the Teith Valley indicate that dwarf-shrub heath was widespread in lowland Perthshire throughout most of the Latelgacial. The freely-drained sites on sands and gravels were probably colonised by Empetrum associations, as indicated by the Interstadial pollen assemblages.

Taking all of the above factors into consideration it is suggested that during the Lateglacial Interstadial there was a tendency towards the development of three broad types of soil: organic soils and gleyed soils in the flatter areas of the valley bottoms and near streams and lakes; the equivalent of Arctic Brown soils as a result of weak podsolisation processes on inclined but not steep slopes of low elevation; and skeletal soils or raw mineral soils on steeper slopes and in upland situations. It is extremely difficult to determine from present evidence the relative importance of each of these three types within southern Perthshire during the Interstadial. Similarly the likely degree of podsolisation, though undoubtedly weak, can only be surmised. A wide diversity of pedogenic factors characterises the Highlands today, and this must also have been the case in the past, and a further difficulty relates to the relatively short time factor involved. However, podsolic soils can be recognised in association with sub-alpine shrub and dwarf-shrub communities in Scotland today, and shallow podsols ('alpine' and 'nano-podsols') are commonly associated with low- and middle-alpine dwarf-shrub and moss heath communities (McVean and Ratcliffe, 1962). The widespread development of such communities during the Lateglacial Interstadial suggests at least the initiation of podsolic processes (embryonic podsolisation - Charlier, 1969) in the better-drained areas.

During the Loch Lomond Stadial ground ice occurred at sea-level in Scotland, and there is evidence for widespread cryoturbation (section 5, above). It is therefore likely that a more direct comparison with present-day arctic soils can be envisaged for this time. Thus even in favourable sites and on inclined slopes a degree of frost-disruption would have been experienced, and saturation as the result of a perennially-frozen substratum would have been widespread. Only skeletal or 'solifluction soils' (McVean and Ratcliffe, 1962), and in places 'frost-churned soils' (James, 1970), would have developed. Much more important to landscape development was the probable total destruction of those soils, more especially the Arctic Brown soils, that developed during the Lateglacial Interstadial.

The climatic improvement at the Lateglacial-Flandrian transition resulted in the cessation of frost-disruption, the disappearance of any existing perennially-frozen substratum, and, also as a result of higher temperatures, greater biogenic activity. During the Flandrian the soil cover of southern Perthshire may have initially resembled that that developed during the Lateglacial Interstadial. However, conditions were not exactly alike, and in the early Flandrian relatively more rapid soil changes may have taken place in the most favourable localities. Soil formation during the Flandrian is a problematic topic which is dealt with in more detail in chapter 12. However, it should be pointed out here that soils would have developed very slowly in Scotland for even today, by world standards, the soils of Scotland are relatively young, many falling into the Entisol (recent) and Inceptisol (in inception) orders of the U.S.D.A. classification (Ragg, 1973).

10. CONCLUSIONS

Lithostratigraphic, biostratigraphic, morphological and chronostratigraphic evidence from Scotland as a whole suggests that at about or shortly before 13,000 B.P. temperatures increased sharply to values at least as warm as those of today, and this resulted in widespread deglaciation in the country. At the same time plant immigration commenced on land, and a seemingly uninterrupted sequence of plant succession developed between ca. 13,000 and 11,000 B.P. Though there is some suggestion of either a very slight or very short climatic oscillation during the early part of this Lateglacial Interstadial phase, which has been equated with the Bölling oscillation of continental north-west Europe, most analyses of Lateglacial sediments in Scotland fail to distinguish this episode.

Following the Lateglacial Interstadial phase a marked climatic deterioration resulted in the Loch Lomond Readvance of glaciers. This period, termed the Loch Lomond Stadial and tentatively dated to between 11,000 and 10,000 B.P., was one of marked vegetational revertence, with a break-up of the closed vegetation cover that had developed during the Interstadial, destruction of Interstadial soils down to sea-level, the production of periglacial morphological features in some areas, and low sea-levels associated with rapid marine erosion.

The close of the Loch Lomond Stadial was marked by a dramatic climatic improvement, achieving temperatures at least as warm as those of today by about 10,000 B.P. This resulted in the widespread stagnation of glaciers, a cessation of soil disturbance, and a vegetation succession that resulted in the replacement of open species-rich grasslands by widespread dwarf-shrub heath and juniper scrub, and eventually by birch woodland, within less than 1,000 years.

Temperature reconstructions, based on coleopteran assemblages, computed firnline altitudes, periglacial features and selected palaeobotanical data, suggest that in southern Perthshire, at least at low elevations, mean July temperature was of the order of 15°C for the early part of the Lateglacial Interstadial, was not in excess of, and was probably about, 12°C for much of the latter half of the Interstadial period, decreased to about 5.5°C during the Loch Lomond Stadial, and was as warm as present-day temperatures by or shortly before 10,000 B.P. Using theoretical temperature lapse rates lower values are calculated for upland areas in southern Perthshire, such as the upper Glen Almond-Corrymuckloch area.

Some inferences are made concerning the development of soils in southern Perthshire during the Lateglacial. It is suggested that weakly-developed podsol profiles may have existed on freely-draining slopes at lower elevations during the Lateglacial Interstadial, related to a soil equivalent to the Arctic Brown soil of present-day arctic areas. However, such suggestions are made cautiously, for climatic conditions during much of the Lateglacial Interstadial were more favourable than those of present-day arctic areas, and an important difference would lie in the absence of frozen subsoil in the Interstadial. During the Loch Lomond Stadial ground ice existed at sea-level of that time and soils may have been more comparable with those of some present-day arctic areas. Frost-disruption at this time destroyed any embryonic soil profiles that may have developed during the Lateglacial Interstadial.

CHAPTER 10

Chronology and terminology of the Lateglacial in Scotland

1. INTRODUCTION

The term 'Late Devensian' has recently been strictly defined in the literature as that period between the chronostratigraphic boundaries of 26,000 and 10,000 B.P. (Shotton and West, 1969; Mitchell et al., 1973). The term refers to the youngest substage and subage of the Devensian Stage and Devensian Age, respectively, and is defined by the biostratigraphic Middle Devensian (interstadial) - Late Devensian (stadial) boundary (26,000 B.P.) and the internationally recognised lower boundary of the Flandrian, 10,000 B.P. The Late Devensian thus includes the time of the build-up and decay of the last major ice sheet to have affected the British Isles, the marked climatic improvement(s) that resulted in the widespread decay of this ice sheet (formerly referred to as the 'Bölling' and 'Alleröd' climatic oscillations), and the much more limited glacial activity of the Loch Lomond Readvance.

There is, however, some inconsistency in the terminology and chronology used to denote the last part of the Late Devensian period. This period is usually referred to as the 'Lateglacial'**, but in the literature this term, through the years, has been given several meanings. For instance, 'Lateglacial' has been used as a general term to cover the period of time covered by the Jessen-Godwin pollen zones I, II and III. Since 'Zone I' deposits may be markedly non-synchronous between individual sites (see chapters 7 and 9) the use of the Jessen-Godwin zonation and hence 'Lateglacial' as defined by that scheme is very imprecise in a time-stratigraphic sense. It has also been used to denote a chronostratigraphic unit, as in Pennington 1975, as a climatostratigraphic unit (Kirk and

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** This term has been used in a variety of forms in the literature, including 'Late Glacial', 'Late-glacial', 'late-glacial', 'late-Glacial', 'lateglacial'; the time-stratigraphic boundaries of these different uses have been widely variable.

Godwin, 1963; Vasari and Vasari, 1968), with inferred climatic characteristics for 'Lateglacial sediments', and has also been used as a general descriptive term applying to local events or episodes, such as glacial retreat stages, shorelines and sea-level changes, vegetational developments, and 'environment' in general.

The term has therefore been applied in a precise way, based on chronostratigraphic definitions, and in an imprecise, informal or descriptive way, and this, together with the fact that a number of different forms of the word are used in the literature (sometimes within the same publication) has resulted, if not in confusion, in a lack of clarity. However, it is such a widely used term, applying to a reasonably specific and important period of time, that the author feels that this term should be retained but defined as strictly as available data for Scotland will permit. As has been shown in chapter 9, very marked climatic changes took place in Scotland between about 13,000 and 10,000 B.P., which differentiate this period of time quite strongly from the remainder of the Late Devensian sub-stage. Since such important environmental changes took place during this transitional period, and since more is known about the Lateglacial than any other part of the Pleistocene, it seems logical to separate out this period of time in the stratigraphic record, though there may be no reason to elevate its status to that of a sub-stage.

The Late-Weichselian subdivision of the continental north-west Europe stratigraphy (Mangerud et al., 1974) has been defined in recognition of the importance of this period in the palaeoenvironmental records of that region. The Late-Weichselian is defined by the chronozone boundaries of 13,000 and 10,000 B.P. Thus the Late-Weichselian, as defined by Mangerud et al., 1974, is not equivalent to the Late Devensian as defined by Mitchell et al., 1973. To classify Lateglacial profiles from Britain as 'Late-Devensian profiles', as in Birks (1973) and Pennington (1975), may only add to any existing confusion, especially when comparing Late-Weichselian and Late Devensian profile subdivisions.

Sufficient data are now available from Scotland to permit an attempt at an independent stratigraphical scheme for Scotland, for a number of radiocarbon dates have recently been published. Since environmental changes throughout the Late Devensian in Scotland need not necessarily have paralleled those of other areas in north-west Europe (see e.g. Birks, 1973; Coope, 1975) an attempt is made in this chapter to construct a Scottish chronology, and to discuss definitions of the terms 'Lateglacial', 'Lateglacial Interstadial' and 'Loch Lomond Stadial' as a Scottish terminology for comparison with chronologies and terminologies of other areas.

A chronostratigraphic subdivision of the Quaternary of the British Isles has been advanced by the Geological Society of London (1967, 1969) and by Mitchell et al.(1973). Recently Mangerud et al. (1974) have outlined a chronostratigraphic scheme for the Quaternary of Norden, and have included a detailed discussion of the Late-Weichselian in particular. However, Mangerud et al. have separated chronostratigraphic criteria and definitions from climatostratigraphic ones, pointing out that climatostratigraphic boundaries "... are not strictly synchronous because climatic changes are complex, and because we do not observe the climatic changes themselves, only the impact of the changes on vegetation, fauna, glaciers, oceans, sediments etc." (1974, p.113). This is, of course, inherently true in a world-wide or even continental sense. However, the alternative approach, of using chronostratigraphic boundaries defined by particular stratigraphic type-sites hardly eases the problem, because stratigraphic units can be widely non-synchronous and very differently related to climatic changes. It would seem reasonable that in such a small area as Scotland climatic changes would have been more or less synchronous, and thus, in order to determine boundaries that have a universal importance (in Scotland) rather than possibly only a local importance, the Scottish Lateglacial boundaries presented here are chosen as close to times of significant climatic change as present knowledge permits.

In terms of climatostratigraphy the Lateglacial should refer to that period between the thermal improvement that led to widespread decay of the Late Devensian ice-sheet and the thermal improvement that resulted in the final disappearance of the ice from Scotland following the Loch Lomond Readvance. With this in mind the evidence for the lower Lateglacial, the Lateglacial Interstadial/Loch Lomond Stadial, and the Loch Lomond Stadial/Flandrian climatostratigraphic boundaries, as they apply to Scotland, are discussed in this chapter.

2. THE LOWER CLIMATOSTRATIGRAPHIC BOUNDARY FOR THE LATEGLACIAL

Six radiocarbon dates have been obtained for basal Lateglacial organic deposits in former or present day lakes, and these are listed in Table 6. These dates, if valid, indicate that much of Scotland was deglaciated by 12,500 B.P., and large areas may have been deglaciated well before then, perhaps as early as 13,000 B.P. However, there are a number of factors that must be taken into account when using dates based on basal organic deposits from terrestrial basins in calculating the time of general deglaciation of Scotland.

(i) With the possible exceptions of Cam Loch and Drymen the dated deposits occur in kettle holes, and it is possible that dead ice could have survived in the depressions for some time after general deglaciation of surrounding areas. Porter and Carson (1971) have reported evidence of drift-mantled ice bodies surviving for 1400 years after the general decay of the Puget Lobe of the Cordilleran Ice-Sheet. It is generally believed that the Late Devensian ice-sheet downwasted in many parts of Scotland (Sissons, 1967a), with large stagnating ice bodies melting out last in major basins and Highland valleys. Since four of the six dates of Table 6 refer to kettle holes within major basins and large Highland valleys it is possible that general glacial decay, and indeed the time of the initial climatic improvement that led to widespread glacial decay, occurred appreciably

TABLE 6 Oldest limnic-terrestrial basal sediments from Scotland

Location and Reference	Material and thickness (cm) of sample	Date (radiocarbon years B.P.) and laboratory reference
Tynaspirit, Perthshire Lowe (this thesis)	gyttja (2.0)	12,750 ± 120 (HV-4989)
Cam Loch, Sutherland (Pennington, 1975)	organic silt (10.0)	12,956 ± 240 (SRR-253)
Loch Droma, Ross and Cromarty (Kirk and Godwin, 1963)	grey-brown silt with macroscopic plant remains (4.0)	12,810 ± 155 (Q-457)
Loch Etteridge, Inverness-shire (Sissons and Walker, 1974)	clay-gyttja	13,151 ± 390 (SRR-304)
Drymen, Stirlingshire (Vasari, 1977)	clay-gyttja	12,510 ± 310 (HEL-160)
Abernethy Forest, Inverness-shire (Vasari, 1977)	sandy-gyttja	12,710 ± 270 (HEL-424)

earlier than these dates indicate.

(ii) The dated organic horizons in each of these six basins do not represent the bottom deposits of the sedimentary sequences, for minerogenic deposits occur beneath each organic horizon. Whether or not such minerogenic sediments represent an appreciable duration of time is unknown, but the possibility cannot be discounted that a significant time-lag between deglaciation and the accumulation of organic sediments may have occurred in one or more of these basins.

(iii) A number of these dates have been obtained on sediment slices several centimetres thick, and it is therefore inevitable that organic matter has been included in the dated samples that is significantly younger than the true date of initial organic sedimentation. This factor is particularly significant in view of the probable slow rate of initial accumulation of organic deposits and the likelihood of high compression in basal deposits. The material dated varies between gyttja, clay-gyttja, sandy-gyttja, and organic silt, and thus rates of sediment accumulation and degree of compaction are probably quite variable between the different sites.

Balanced against these points there is the possibility that some of the dates may be liable to error due to the "hard water effect", as, for instance, is suspected for the date from the Abernethy Forest site (Vasari, 1977). In addition, four of the dates are based on material obtained by the bulking of multiple shot samples, the exceptions being Loch Droma and Cam Loch. In the case of those dates based on thin (less than 5 cm) sediment slices this may also introduce some error. Thus the interpretation of these six dates is far from straightforward, and many more dates are required to gauge fully the importance of each of the possible sources of error. It is suggested that until more dates are forthcoming, the six dates given in Table 6, if valid, should be regarded as minimal for deglaciation of Scotland.

In addition to the six dates for basal organic sediments, a date of 12,940 ± 250 B.P. has been obtained for a piece of wood in a peat layer at Roberthill, near Lockerbie (Bishop, 1963), while the oldest dates for the inner layers of marine shells from the Clyde estuary are about 12,600 B.P. (Bishop and Dickson, 1970; Peacock, 1971). These dates are also likely to be minimal for deglaciation since substantial thicknesses of minerogenic sediments occur below the dated horizons, and in the case of the date from Lockerbie time must be allowed for the immigration and growth of trees.

Even though these dates provide evidence for the timing of ice-wastage they do not necessarily relate to the thermal improvement that led to deglaciation. It is probable that there was a significant time-lag between thermal improvement and deglaciation from a thick mass of ice, and this time-lag may have been quite variable for different parts of Scotland as deglaciation is time-transgressive. In addition it is also possible that at least initially deglaciation resulted not from thermal improvement but from, for example, changes in precipitation values. These dates are thus not only minimal for deglaciation, but they are also likely to be unsatisfactory as climatostratigraphic indicators.

In an attempt to define a climatostratigraphic lower boundary for the Lateglacial the following lines of evidence can be considered. In terms of changes within the northern hemisphere in general, Mercer (1972) has suggested that the main global warming that marks the end of the Pleistocene occurred at about 14,500 to 14,000 B.P. From work on ocean sediments in the North Atlantic Ruddiman and McIntyre (1973) have suggested that the change from dominantly polar to non-polar foraminifera and from low to high fine carbonate content of marine sediments occurred about 13,500 B.P. off the coast of Britain. In an attempt to determine Lateglacial climatic boundaries more accurately Pennington (1975, 1977) has employed absolute pollen analysis at a radiocarbon-dated profile from Cam Loch in Sutherland. This work is important as a major conclusion from it is that at two widely separated sites (Cam Loch, and Blelham Bog in north-west England) significant vegetational changes took place at about 13,000 B.P., thus suggesting that this chronozone boundary, identified as an important horizon on the continent (Mangerud et al., 1974), may be an important climatic one for British stratigraphy. Partial support for this hypothesis can be found in coleopteran studies which suggest that the transition from an arctic climate to the thermal maximum of the Lateglacial Interstadial was remarkably sudden and occurred by 13,000 B.P. (Coope, 1975; Bishop and Coope, 1977).

Taken together this evidence would seem to suggest that though a general global warming may have occurred somewhat earlier, a marked thermal improvement occurred in the vicinity of the British Isles at about 13,000 B.P. There are, however, a number of problems. Firstly, Pennington's conclusions rest on the assumption that the increased Juniperus pollen influx values at Blelham Bog and Cam Loch are necessarily related to increased flowering of juniper already present in the basins. There is the strong possibility that the sudden increase in Empetrum and Juniperus values recorded are related to delayed immigration of the plants into the respective areas. Secondly, the basal deposits at Blelham Bog have been dated to 14,330 ± 230 B.P., implying very early deglaciation of this particular basin. The date of 13,450 ± 220 B.P. from Blelham Bog used as the basis for the age of the boundary indicating climatic improvement requires a subtraction of two standard deviations to fit with the concept of a climatostratigraphic boundary at 13,000 B.P. The corresponding date at Cam Loch, 12,956 ± 240 B.P., has been obtained from a 10 cm thick sample and may only date the beginning of accumulation of organic sediments at this site and not the date of climatic improvement (see above). Thirdly, it is argued (Bishop and Coope, 1977) that coleoptera react much more quickly to climatic changes than do plants, and yet the faunal assemblages from south-west Scotland that react remarkably suddenly to climatic changes at ca. 13,000 B.P. are dated to 12,940 ± 250 B.P. by a piece of wood, which appears contradictory. Fourthly, Ruddiman and McIntyre have based their date of the change in ocean temperature conditions on extrapolation of sedimentation rates from ocean sediments that lie stratigraphically above those that are critical to their hypothesis. In addition, there is the possibility that changes in ocean temperatures may not parallel terrestrial or land surface temperature changes, though usually the oceanic climate of the British Isles is very much linked to changing ocean conditions.

It appears, therefore, that the apparently rapid thermal improvement that resulted in final widespread decay of the Late Devensian ice-sheet and in major biotic displacements in Scotland was initiated by 13,000 B.P. However, if the possibility of time-lag in biotic changes and in sedimentation are considered, and if the problems of interpretation of available radiocarbon dates are also considered, then the evidence can be interpreted as indicating climatic improvement before 13,000 B.P., and perhaps well before then. Unfortunately there is at present insufficient evidence for defining the time of the beginning of this thermal improvement, but current evidence from the British Isles as a whole suggests that it occurred between about 14,000 and 13,000 B.P. (Coope, pers. comm.). Certainly the interpretation of the chronostratigraphic boundary of 13,000 B.P. as an important climatostratigraphic one for Scotland appears somewhat premature.

3. SUBDIVISION OF THE LATEGLACIAL: THE LATEGLACIAL INTERSTADIAL/LOCH LOMOND STADIAL BOUNDARY

It has been argued in chapters 8 and 9 that only two subdivisions of the Lateglacial can be justified, the Lateglacial Interstadial, and the Loch Lomond Stadial. Evidence for an equivalent to the Bölling oscillation of continental north-west Europe remains debatable. It has been suggested elsewhere (Vasari, 1977) that some regional disparity occurred in Scotland as regards the intensity of this possible oscillation, such that northern and north-eastern parts of the country may have experienced a climatic oscillation during the Lateglacial Interstadial more strongly than other parts of the country. However, it would seem that the amplitude of this oscillation was either very small in comparison with the total amplitude of the Lateglacial period (Pennington, 1977), or it was of only a very short duration. Certainly the bulk of the evidence from Scotland suggests that the Lateglacial Interstadial was a period of fairly stable climatic conditions. Coleopteran evidence (Bishop and Coope, 1977) suggests that a thermal maximum occurred early in the Lateglacial Interstadial, and that climatic deterioration was more or less continuous and gradual from about 12,000 B.P., culminating in the intensely cold Loch Lomond Stadial, though this deterioration may have become more intense at about 11,000 B.P.

Since there appears to have been a gradually deteriorating climate throughout the latter part of the Lateglacial Interstadial it is extremely difficult to define a chronostratigraphic boundary for the Lateglacial Interstadial/Loch Lomond Stadial transition that is important in climatostratigraphic terms. The lower boundary of the main Lateglacial revertence phase in British pollen diagrams ('Zone III'; 'Younger Dryas'; Loch Lomond Stadial) has generally been assumed to be synchronous with the Alleröd/Younger Dryas boundary of continental Europe, dated generally to between 11,000 and 10,800 B.P. (Iversen, 1953; Berglund, 1966; Tauber, 1970; Mangerud <u>et al</u>., 1974). Support for the concept of synchroneity between Britain and north-west Europe has been argued on the basis of an extremely small number of radiocarbon dates (Godwin and Willis, 1959). Pennington (1975, 1977) has accepted the chronozone boundary of 11,000 B.P. as defining the Alleröd/Younger Dryas boundary at Cam Loch, but the published radiocarbon dates from Cam Loch are not critically related to the important biostratigraphic horizon indicating climatic deterioration.

Six radiocarbon dates are available from Scotland that are on or close to important biostratigraphic horizons interpreted as indicating the beginning of the main vegetational revertence phase equated with the Loch

TABLE 7 Radiocarbon dates of terrestrial biostratigraphic boundaries indicating beginning of Lateglacial vegetational revertence in Scotland

Location and Reference	Material and thickness (cm) of sample	Date (radiocarbon years B.P.) and laboratory reference
Abernethy Forest, Inverness-shire (Vasari, 1977)	banded gyttja (10.0)	11,260 ± 240 (HEL-423)
Drymen, Stirlingshire (Vasari, 1977)	gyttja (5.0)	12,060 ± 320 (HEL-161)
Tynaspirit, Perthshire (Lowe, this thesis)	gyttja (2.0)	11,385 ± 290 (HV-4987)
Loch Etteridge, Inverness-shire (Sissons and Walker, 1974)	gyttja (1.5)	10,764 ± 120 (SRR-302)
Loch Kinord, Aberdeenshire (Vasari, 1977)	gyttja/clay-gyttja (10.0)	10,640 ± 260 (HEL-419)
Garral Hill, Banffshire (Godwin and Willis, 1959)	silty Hypnum peat (5.0)	10,800 ± 230 (Q-104)

Lomond Stadial. These are listed in Table 7. Again there are difficulties in comparing these dates. First, rather large standard deviations are associated with some of these dates. Secondly, two of the dates are based on 10 cm thick sediments slices (see above), though in this case the larger samples may tend to make the dates older than the horizon under scrutiny. Of the dates based on thinner sediment slices, which might be regarded as more critical (Tynaspirit, Loch Etteridge), there are marked discrepancies between them, with no overlap in the standard deviations.

There is no clear boundary indicated by these dates, and certainly there is poor support for the importance of the continental stratigraphic horizon of 11,000 - 10,800 B.P. Either the radiocarbon dating method may be too inaccurate and involve too many possible sources of error to attempt precise correlations of this nature (see Conclusions), or there is the possibility of widely non-synchronous environmental effects of the deteriorating climate of this time. Vasari (1977) has suggested that there were regional differences in Scotland regarding the time of vegetational response to climatic deterioration. It has been suggested from the evidence in southern Perthshire (Chapters 8 and 9) that climatic deterioration may have already affected the local vegetation prior to the biostratigraphic boundary from Tynaspirit 2 dated to 11,385 ± 290 B.P. From a number of considerations, including glaciological ones, Sissons (1974a, p.320) concluded that "... it appears that the Loch Lomond Readvance began before, perhaps well before 10,800. It may also be inferred, in view of the variations in relief and precipitation, that glaciers began to develop at different times in different places." In the same way, as a result of the immense variation in relief, relative shading, soil depth and parent material, precipitation, etc., that is characteristic of Scotland today, it is perhaps only to be expected that other environmental effects of the continuous climatic deterioration since 12,000 B.P., such as the opening up of the closed vegetation cover, the erosion of soils, gelifluction, were also time-transgressive.

In spite of Bishop and Coope's (1977) evidence for an early beginning to climatic deterioration in the Lateglacial Interstadial, there are at present insufficient radiocarbon dates to determine whether or not there is a significant chronostratigraphic horizon that has important implications for Scotland as a whole. With present information the date from Drymen seems anomalous, and averaging the remainder of the dates suggests a date close to 11,000 B.P. In view of discussions above, however, this may be an invalid procedure. Thus though there is evidence of an onset to climatic deterioration earlier than 11,000 B.P. there is at present insufficient justification for placing the Lateglacial Interstadial/Loch Lomond Stadial climatostratigraphic boundary any earlier than the chronostratigraphic boundary of 11,000 B.P. Bishop and Coope (1977) suggest that climatic deterioration began before 11,000 B.P. but became more intense at about this time.

The term Loch Lomond Stadial is used in place of Younger Dryas or Zone III since, as a climatostratigraphic unit, it may eventually have a different definition. The Stadial is named after the Loch Lomond Readvance, a now well-established term in the literature. In addition to the problems of defining a lower boundary to the Loch Lomond Stadial there are also problems in deciding the upper Stadial boundary in Scotland.

4. THE LOCH LOMOND STADIAL/FLANDRIAN TRANSITION

Since the upper horizon for the Late Devensian sub-stage has been placed at 10,000 B.P. (Mitchell et al., 1973), the internationally recognised chronozone boundary marking the beginning of the Flandrian (Suggate and West, 1967; Mangerud et al., 1974), this has been accepted as the upper chronozone boundary for the Lateglacial in Scotland. However, available evidence reveals difficulties. The 10,000 B.P. horizon is an arbitrary limit, and need not necessarily have a close relationship with biostratigraphic or climatostratigraphic changes in different parts of north-west Europe (e.g. Mangerud et al., 1974). Thus it is perhaps only to be expected that this boundary may have little environmental relevance for specific localities. A number of radiocarbon dates are now available from Scotland for biostratigraphic boundaries indicating a close to the harsh climatic conditions of the Loch Lomond Stadial. These dates are listed in Table 8. The dates are based on organic samples from biostratigraphic boundaries indicating the end of the major vegetational revertence phase, thus implying climatic improvement, and in most cases they coincide with or are close to a maximum of Juniperus pollen in the respective pollen diagrams. Clearly there is some disparity in these dates.

In comparing these dates, a number of factors should be considered.

(i) There is the possibility that the oldest dates are subject to "hard water error". Most of the "old" dates derive from sites in southern Perthshire, and are described earlier in this thesis. There are no reasons to suspect any error of this nature in any of these samples, although calcareous nodules and a calcareous cementing matrix have been reported from the Teith Formation of the Old Red Sandstone in the Callander area. However, these are not common (Francis et al., 1970). Further, a date recently obtained from terrestrial moss fragments (see below) supports the Rannoch Moor basal date and thus adds support to the hypothesis that parts of Scotland were deglaciated from Loch Lomond Readvance ice quite some time before 10,000 B.P.

(ii) The youngest dates may be subject to contamination, and this appears to have been the case at Blackness (Walker, 1975a).

(iii) Younger dates may reflect continued minerogenic inwash following the close of the Loch Lomond Stadial, as has been suggested for sediments at Loch Etteridge, where it is thought that continued solifluction accounts for the young 'Stadial/Flandrian' date reported from this site (Sissons and Walker, 1974).

TABLE 8 Radiocarbon dates of terrestrial biostratigraphic boundaries indicating end of Lateglacial vegetational revertence in Scotland

Location and Reference	Material and thickness (cm) of sample	Date (radiocarbon years B.P.) and laboratory reference
Amulree, Perthshire (Lowe, this thesis)	gyttja (2.0)	10,770 ± 90 (HV-5644)
Mollands, Perthshire (Lowe, this thesis)	gyttja (2.0)	10,670 ± 85 (HV-5647)
Tynaspirit, Perthshire (Lowe, this thesis)	gyttja (2.0)	10,420 ± 160 (HV-4985)
Cam Loch, Sutherland (Pennington, 1975)	organic mud	10,226 ± 190 (SRR-247)
Blackness, Angus) (Walker, 1975a)	gyttja (1.5)	9,490 ± 160 (HV-5649)
Rannoch Moor, Argyllshire (Lowe and Walker, in press)	gyttja (1.0)	10,520 ± 330 (BIRM-723)
Loch of Park, Aberdeenshire (Vasari, 1977)	gyttja/clay gyttja (10.0)	10,280 ± 220 (HEL-416)
Loch Kinord, Aberdeenshire (Vasari, 1977)	gyttja (10.0)	10,010 ± 220 (HEL-420)
Abernethy Forest, Aberdeenshire (Vasari, 1977)	gyttja (10.0)	10,230 ± 220 (HEL-422)
Drymen, Stirlingshire (Vasari, 1977)	gyttja/clay-gyttja (16.0)	10,010 ± 230 (HEL-162)
Lochan Coir a' Ghobhainn, Isle of Skye (Birks, 1973, reinterpreted by Vasari, 1977)	diatomaceous fine-detritus gyttja mud (2.5)	10,254 ± 220 (Q-955)
Loch Cuithir, Skye (Vasari, 1977)	clay-gyttja (10.0)	10,060 ± 270 (HEL-504)
Loch Etteridge, Inverness-shire (Sissons and Walker, 1974)	clay-gyttja (4.0)	9,405 ± 260 (SRR-301)
Murraster, Shetland (Johansen, 1975)	detrital gyttja (13.0)	10,400 ± 100 (K-1865)

(iv) A number of the dates are based on thick sediment slices, and there is a strong possibility that this has resulted in the incorporation of organic material that is significantly younger than the climatostratigraphic and the precise biostratigraphic boundary that marks the end of the Loch Lomond Stadial.

(v) At least two of the dates (Mollands and Rannoch Moor) are basal organic samples from kettle holes occupied by Loch Lomond Readvance glacier ice. As discussed above, there is the possibility that ice may have survived within the kettle holes until some time after the general deglaciation of the Loch Lomond Readvance glaciers.

A number of the dates listed in Table 8 are based on very thin sediments slices, viz. Amulree (10,770 ± 90 B.P.), Tynaspirit (10,420 ± 160 B.P.), Mollands (10,670 ± 85 B.P.), Loch Etteridge (9,405 ± 260 B.P.), Blackness (9,490 ± 160 B.P.), and Lochan Coir a' Ghobhainn (10,254 ± 220 B.P.). In addition, though the date recently obtained from Rannoch Moor (10,520 ± 330 B.P.) was of gyttja, stratigraphically above this gyttja a date of 10,290 ± 180 B.P. has been obtained from terrestrial moss fragments (Lowe and Walker, in press). Of these dates Blackness and Loch Etteridge can be dismissed since they are not particularly useful for dating the climatostratigraphic boundary for the close of the Loch Lomond Stadial, for reasons given above. Of the remaining five, four are clearly at variance with the accepted age of the close of the 'Zone III' or Younger Dryas stadial of the continental north-west Europe scheme. Since these four dates relate to four different sites, and at one site support can be found from a date based on terrestrial macrofossils, the possibility cannot be discounted that, at least for some sites, biostratigraphic changes as a result of climatic improvement may be quite variable in age throughout Scotland. In addition, the climatostratigraphic boundary may be earlier than the boundary of 10,250 B.P. suggested by Berglund (1966) and Godwin (1975) to mark the end of the Younger Dryas stadial. From the

Scottish dates in general (Table 8) climatic improvement certainly seems to have occurred before 10,000 B.P., reinforcing the fact that this chronozone boundary is an arbitrary one in relation to Scottish Lateglacial environmental history.

If the early dates for the biostratigraphic boundaries marking the end of the cold Loch Lomond Stadial are confirmed by further research then it may be necessary to subdivide the Loch Lomond Stadial into two periods. Pennington (1977) has suggested this for the Stadial sediments of Cam Loch, with a period of low temperatures during which the most severe climatic conditions (and environmental effects) occurred, dated to between 11,000 and 10,400 B.P., followed by a period of rapid climatic amelioration between 10,400 and 10,000 B.P. The time-transgressive dates from Scotland would seem to support this hypothesis. The climatostratigraphic boundary that marks the earliest dates for climatic improvement is tentatively placed at 10,500 B.P., in view of the two dates slightly in excess of 10,400 B.P., and the possibility of time-lags. The dates from Mollands and Amulree require further testing. A transition phase, when glacial decay, vegetational successions and soil stability progressed time-transgressively in Scotland, may have occurred between 10,500 and 10,000 B.P.

5. CONCLUSIONS

If the interpretation of the radiocarbon dates outlined above can be accepted as valid, and if the biostratigraphic interpretations reviewed in chapter 9 are correct, then they indicate a two-fold climatostratigraphic scheme for the Lateglacial of Scotland. The lower climatostratigraphic boundary appears to be older than 13,000 B.P., but is extremely difficult to define. There is evidence for marked climatic improvement by 13,000 B.P., but climatic deterioration leading to the Loch Lomond Readvance of glaciers was initially gradual, and thus a Lateglacial Interstadial/ Loch Lomond Stadial climatostratigraphic boundary is difficult to define. Coleopteran evidence suggests that climatic deterioration began as early as 12,000 B.P. but became more intense at about 11,000 B.P. There is thus insufficient justification, at present, for placing the Lateglacial Interstadial/Loch Lomond Stadial climatostratigraphic boundary any earlier than the chronostratigraphic boundary of 11,000 B.P. However, the internationally recognised lower Flandrian boundary of 10,000 B.P. has little relevance for the climatostratigraphy of Scotland, for climatic improvement, marking the close of the Loch Lomond Stadial, appears to have occurred significantly earlier than 10,000 B.P.

An interesting point concerning the radiocarbon dates for the Lateglacial in Scotland is that, taken collectively, they span the whole period of the Lateglacial when the standard deviation overlaps are considered. This perhaps indicates that the radiocarbon dating method may not be accurate enough to differentiate the important horizons of environmental change that occur within the relatively short time-span of the Lateglacial. Further, a large number of these dates have been based on gyttja samples, and doubt has recently been expressed concerning gyttja as a suitable material for radiocarbon assay (R.E.G. Williams, pers. comm.). Thus, though the problems of time-transgressive phenomena are logical concepts in view of our growing understanding of the nature of environmental changes, it may be some time before confidence can be placed on the supposed demonstration (by radiocarbon dating) of time-transgressive boundaries. Many more radiocarbon dates are required, but these dates must be viewed critically, not only for the possibility of errors inherent in the dating method itself, but also for the variety of materials and often different thicknesses of samples that are assayed.

CHAPTER 11

Vegetational history during the Flandrian in southern Perthshire and its implications

1. INTRODUCTION

The sequence of local pollen assemblage zones for each of the sites in southern Perthshire has been discussed in chapter 7 and a suggested correlation of Flandrian pollen zones is provided in Table 4. It was suggested in chapter 7 that marked contrasts in vegetational composition appear to have occurred within southern Perthshire during the Flandrian, and that there may have been some significant time differences in the immigration of certain elements of the flora between upland and lowland sites. However, a major problem in comparing the Flandrian biostratigraphic zones is the lack of chronostratigraphic data, for radiocarbon dates are available only for the Lateglacial/Flandrian transition sediments and horizons marking the first appearance of hazel at three of the sites.

A number of authors have pointed out that in the northern and western parts of the British Isles great difficulties are encountered in attempting to delimit the early Postglacial pollen zones IV, V and VI as defined by Godwin in 1956 (Donner, 1957; Smith, 1961; Watts, 1963; Vasari and Vasari, 1968; Moar, 1969a; Pennington _et al_., 1972; Birks, 1973). Thus Vasari and Vasari (1968) defined a "transition zone III-IV" to denote the characteristic _Juniperus_ and _Empetrum_ maxima that mark climatic improvement following the Loch Lomond Stadial, and "the zone IV proper", to denote the _Betula_ maximum that followed. However, Godwin (1975) has equated the _Juniperus_-_Empetrum_ vegetation phase of northern Scotland with Postglacial zones IV and V for the British Isles (see Table 1). This perhaps illustrates the problem of using biostratigraphic criteria for correlation. The shrub-dominated vegetation associations that colonised the open herbaceous communities following the Loch Lomond Stadial may have remained dominant for thousands of years in the extreme northern parts of Scotland, but may have been replaced relatively quickly by birch forest in southern localities. Similarly, disparities may arise between different sites in the Highlands, where birch forest may have colonised lower-lying sheltered valleys with favourable aspect relatively quickly, but a shrub-dominated vegetation may have persisted at higher, more exposed localities. For instance, Vasari and Vasari (1968) found that theee different types of vegetation existed during their III-IV transition zone, depending on geographic position, which in turn appears to have determined the relative importance of juniper and birch shortly after the Loch Lomond Stadial. It is logical to assume that there was a time-lag in the development of birch forest following the Loch Lomond Stadial, and that the magnitude of this time-lag would have depended on the rate of migration of birch, the distance from the refugia of birch, the altitude of the site under scrutiny, and the complicated set of local factors affecting pedogenesis at a specific locality. The same would hold true for the immigration of hazel and of other woodland species. For confident correlations of biostratigraphic horizons chronostratigraphic data are therefore essential.

A further difficulty exists in the use of terminology. As the use of regional biostratigraphic horizons for inter-regional correlation requires caution, so too does the use of chronostratigraphic terminology. For instance, the term 'Flandrian' is a chronostratigraphic unit with an internationally-accepted lower chronostratigraphic boundary. Its subdivision should also therefore be on a chronostratigraphic basis, preferably according to internationally agreed horizons. The use of terms 'Early Flandrian', 'Middle Flandrian' and 'Late Flandrian', defined on the basis of local vegetational succession, would thus seem somewhat inconsistent (e.g. O'Sullivan, 1974).

West (1970) has recommended a three-fold subdivision of the Flandrian where the Early Flandrian is defined as the phase of immigration and succession of pioneer vegetation, the Middle Flandrian the phase of the development of the dominant forest type, and the Late Flandrian the period since the onset of major human impact on vegetation. These are thus biostratigraphic boundaries. The lower boundary of the Late Flandrian as defined by West (1970) has been found to be broadly synchronous across the British Isles (Hibbert et al., 1971; Smith and Pilcher, 1973), but the immigration and expansion of tree species in different parts of the British Isles has been diachronous (see chapter 12). For instance, Alnus expansion and immigration occurred relatively late in the Scottish Highlands in comparison to England and southern Scotland (Moar, 1969c; H.H. Birks, 1970, 1972; Hibbert et al., 1971; Pennington et al., 1972; O'Sullivan, 1974). Hafsten (1970) has demonstrated clearly the metachroneity of the zone boundary IV/V of Jessen (1938) in Scandinavia. "The regressive age of this zone with northern latitude is strikingly clear and of the order of a thousand years or more. The time-lag may even be up to 3,000 years in extreme cases" (p.280). This zone boundary is defined by the change in the relative importance of birch and pine and by the first significant appearance of hazel.

The lower boundary of the Flandrian is defined at 10,000 B.P., but there are problems in stratigraphic nomenclature where this chronostratigraphic boundary has no relevance in terms of local environmental changes (see chapter 10). The Early Flandrian/Middle Flandrian boundary as defined by West (1970) is likely to be metachronous for different parts of the British Isles, with the greatest metachronism likely to be in the northern extremes and the Highlands of Scotland.

There is little evidence for Late Flandrian developments in southern Perthshire, using the definition of West (1970). The Flandrian pollen zones presented in this thesis approximate to the Early Flandrian and Middle Flandrian, though these terms are avoided because of the difficulties discussed above and in earlier chapters. Instead, biostratigraphic terminology is preferred in comparing the pollen zones from southern Perthshire, and a possible chronology for vegetational development is discussed in chapter 12. The term 'early Flandrian' has been used in this thesis to refer to that period during which the open herbaceous communities of southern Perthshire, established during the Loch Lomond Stadial, were replaced first by shrub-dominated communities and then by birch forest. The term 'Early Flandrian' has been avoided, where the use of a capital letter, indicating a formal stratigraphic unit, should require (in the author's opinion) strict chronostratigraphic definitions. Similarly, 'middle Flandrian' and 'late Flandrian' are used in an imprecise way, though in general terms they may approximate in age to corresponding divisions in other regions.

2. THE IMMIGRATION OF BIRCH AND ESTABLISHMENT OF BIRCH FOREST

Following the early Flandrian phase of shrub-dominated vegetation, where *Juniperus*, *Salix* and *Empetrum* were the main components, birch immigrated into southern Perthshire and dominated the vegetation. In those diagrams based on a tree pollen sum, birch accounts for over 90% of arboreal pollen (zone Clg, Fig. 19; Tlf, Fig. 16; Moc, Fig. 24; and Amlf, Fig. 21). The generalised diagrams in these figures, and the birch percentages in Figs. 17, 22 and 25, show that birch pollen grains account for up to 60% of total land pollen recorded for this phase. The marked declines in the percentages of shrub pollen recorded at each site are interpreted as indicating the suppression of shrubs by the development of dense forest, though forest may have been dense only locally. Especially marked in each diagram is the dramatic decline in juniper pollen percentages. Juniper reaches maturity very quickly, has a wide ecological amplitude, is able to grow well on relatively unstable ground, and can thrive within forests (Iversen, 1954; Vasari and Vasari, 1968). However, it shows a clear preference for open, light vegetation in Fennoscandia (Kujala, 1958) and is normally associated with the upper forest limit in its natural distribution in Scotland (McVean, 1961).

It is apparent, therefore, that with the establishment of the birch-dominated phase (Table 4) juniper could not compete with birch and in general became restricted to higher slopes above the developing birch forest. However, both juniper and Salix are significantly represented in the diagrams throughout this phase, and these shrubs are likely to have continued to grow on lower slopes as an understorey in the birch forest. In the lower lying sites of the Teith Valley, Salix is more strongly represented than Juniperus, and is likely to have been the more dominant shrub in the birch forest at lower altitudes. At the upland site of Amulree juniper is more strongly represented (Fig. 21, zone Am1f; Fig. 22, zone Am2g), indicating a lighter birch forest, or possibly co-dominant birch and juniper stands in this area at that time. Species of tree birch are prolific pollen producers (Andersen, 1970), and it is therefore likely that juniper and willows are under-represented in the pollen diagrams from southern Perthshire.

To what extent closed birch woodland developed in southern Perthshire is difficult to establish. The dominance of birch pollen is a noticeable feature in the early Flandrian at each site, but because of problems of differential relative pollen production and pollen representation in both arboreal and non-arboreal species, it is difficult to translate such high percentages in terms of actual ground cover. Faegri and Iversen (1964) suggest that when the non-arboreal pollen component in a diagram is continuously less than 10% of total arboreal pollen then continuous closed forest is indicated. If this assumption is correct, then this would indicate that birch forest formed a light cover at each of the sites in southern Perthshire, and especially at Amulree. It is likely that the density of the birch canopy was extremely variable, being locally dense but in other places open or absent, depending on edaphic variation and other local ecological factors.

There is macrofossil evidence for the presence of both Betula pubescens and B. pendula in the early Flandrian of Aberdeenshire (Vasari and Vasari, 1968). It seems reasonable to assume therefore that both species were present in southern Perthshire at that time. However, macroscopic evidence from Britain as a whole indicates the greater prevalence of B. pubescens at that time (Godwin, 1975), this being a more northerly species than B. pendula. B. pubescens is the more prevalent species in the Scottish Highlands today, and birchwood is either found principally in two noda, a Vaccinium-rich birchwood and a herb-rich birchwood, or is found in association with oak forest (McVean and Ratcliffe, 1962). Occasionally associated with the Vaccinium-rich birchwood is a tall-shrub layer dominated by Juniperus communis, which can be locally dominant (McVean, 1958), and surface pollen counts from these communities, or close to these communities, may provide relevant data for more reliable interpretations of early Flandrian pollen assemblages.

According to the radiocarbon dates the birchwood phase occurred at Tynaspirit between about 10,400 and 9,250 B.P. (Fig. 17), at Mollands between 10,480 and 9,400 B.P. (Fig. 25), and at Amulree between about 10,250 and 9,100 B.P. (Fig. 22). At each site the lower date relates to the decline of the importance of juniper and the upper date to the first appearance of Corylus pollen in the diagrams (see below). These dates support each other in indicating the establishment of birch woodland throughout southern Perthshire shortly after 10,400 B.P., and its dominance in both lowland and upland sites by about 9,100 B.P. The slightly later dates recorded at Amulree are consistent with the concept that slightly later birch immigration and expansion would be expected at this site which is both higher in altitude and farther north. If valid, the dates indicate the rapid spread of birch into the Highland valleys of the Southern Grampians, and the establishment of birch woodland on uplands as well as in the main valleys (see chapter 12). As discussed in earlier chapters, however, the dates should be regarded as questionable until more evidence is forthcoming.

3. THE IMMIGRATION AND EXPANSION OF HAZEL, AND THE POSSIBLE UNDER-REPRESENTATION OF TERRESTRIAL PLANT SPECIES

Following the establishment of birch woodland, the next major landscape change in southern Perthshire was the rapid colonisation of lowland and upland sites by hazel. In Flandrian pollen diagrams from each of the five sites considered (Figs. 16, 19, 21, 24 and 26) there is a clearly marked birch-hazel pollen zone. In the diagrams for sites from the Teith Valley Corylus percentages are commonly in excess of 100% of arboreal pollen in the Betula-Corylus zone (Table 4), and in the upland sites of Glenturret and Amulree, though percentages are lower in general than in the Teith Valley diagrams, some percentages in excess of 100% arboreal pollen are recorded.

Hazel, a shade-tolerant shrub, is a common understorey shrub today in mature broad-leaf deciduous forest. The evidence from southern Perthshire suggests that hazel spread quickly throughout the established birchwood, and perhaps became a dominant canopy species in some areas. However, in interpreting the large Corylus pollen percentages two major problems should be taken into account. Firstly, it is extremely difficult to separate pollen grains of Corylus from those of Myrica gale, so much so that a number of palynologists now record 'Corylus-Myrica'(e.g. Pennington et al., 1972) or 'coryloid' pollen curves (e.g. O'Sullivan, 1974). Myrica gale is a common component on bog surfaces in the Scottish Highlands today, and occurs on the surfaces of the bogs at Tynaspirit and Glenturret. However, it appears likely that the high percentages of 'coryloid' pollen are attributable mainly to Corylus grains at least in the early Flandrian, for Myrica did not become important until the middle Flandrian (Godwin, 1956; Pennington et al., 1972). Secondly, hazel produces pollen grains in great abundance and begins to flower at an early age (Godwin, 1975). It is likely, therefore, that hazel pollen would be strongly over-represented in pollen spectra.

With further regard to the first difficulty, Godwin (1975) points out that macrofossils of hazel are common from all parts of the British Isles, hazel nuts being possibly the most commonly recognised fossil in peat and alluvial deposits. In addition, he states that "... unqualified '<u>Corylus</u>' amounts to 75 per cent of the records in all zones and the records are so numerous that they can safely be considered as essentially reflecting the history of hazel" (<u>op. cit</u>., p.269). As regards the problem of over-representation of <u>Corylus</u> pollen, it appears that although hazel is a shade-tolerant plant, it is only moderately so (Iversen, 1960). Where it forms an understorey shrub, its flowering is reduced and its relative pollen percentages are relatively low (Jonassen, 1950). Only where it occurs as a canopy species, either exclusively or in association with birchwood, are high relative pollen percentages found in surface samples (Birks, 1973). Thus extremely high relative pollen percentages of <u>Corylus</u>, as in the pollen diagrams from southern Perthshire, are likely to reflect hazel as a canopy species. This further indicates the likelihood that the birchwood that had developed in the early Flandrian could only have formed closed birch forest locally, if at all.

The <u>Corylus</u> pollen curves in the diagrams from southern Perthshire are interpreted as indicating predominantly pollen of hazel, though pollen of <u>Myrica gale</u> is probably also included. Macrofossil records from other parts of the British Isles indicate that the <u>Corylus</u> pollen are almost exclusively of the species <u>C. avellana</u> (Godwin, 1975). Hazel probably spread throughout southern Perthshire colonising areas that had remained forestless and invading birch forest as an understorey shrub. The exceedingly high percentages of <u>Corylus</u> in each of the five sites suggests that hazel not only successfully invaded the birch forest, but locally existed as a canopy species in southern Perthshire. The percentages recorded at Mollands (values of 408% and 533% of arboreal pollen are recorded here) support this latter statement.

Again it is difficult to interpret this <u>Betula</u>-<u>Corylus</u> phase in terms of the likely ground cover commanded by birch and hazel. Since both are prolific pollen-producers, over-representation of pollen is highly likely, though it is not possible to gauge the effect of this factor. In the Teith Valley sites the combined tree and shrub pollen percentages consistently approach 90% in the Betula-Corylus zone, which in view of Iversen's criteria (see above) could indicate a closed tree/shrub canopy in the Teith Valley at that time. The combined tree-shrub pollen totals are also high in the upland sites of Glenturret and Amulree. In all of the diagrams pollen of Juniperus fall to a value consistently under 10% arboreal pollen in the Betula-Corylus zone, and this would seem to indicate that juniper, which is a light demanding shrub, was unable to compete with the invading Corylus, or declined under a dense combined birch-hazel canopy. However, the reduced percentages of Juniperus pollen may in part result from the under-representation of juniper pollen in relative pollen diagrams. Absolute pollen counts are required to test this hypothesis. It appears, however, that willows were able to compete much more strongly than juniper with the relatively dense birch-hazel stands; this may have been as a consequence of the tendency of many willow species to concentrate on wetter ground. Percentages of Salix pollen are maintained at much higher values than Juniperus in the Betula-Corylus zone, and this is especially noticeable at Mollands and Glenturret (Figs. 24 and 26).

There is the possibility that some tree or shrub genera that may have been common in Scotland in early Flandrian times are severely under-represented in the pollen diagrams. For instance pollen grains of Populus have been identified at Mollands and Tynaspirit. Populus grains are exceedingly fragile and hence liable to destruction as a result of processes of sedimentation (Sangster and Dale, 1961, 1964). Thus records of a few grains or even a single grain in a spectrum may be highly significant. Pollen records of Populus are sparse, but those available suggest that the genus has been present in the British Isles since Lateglacial times and that they most probably represent the aspen, P. tremula (Godwin, 1975). The records of Populus from Mollands and Tynaspirit suggest that the aspen may have been able to compete successfully in the predominant birch-hazel woodland.

There are also poor palaeobotanical records of Sorbus from the Lateglacial and early Flandrian of the British Isles. A few macrofossil finds of S. aucuparia are of Lateglacial age (Godwin, 1975), but pollen records of Sorbus are so far mainly from sites in northern Britain (Franks and Pennington, 1961; Birks, 1973). As rowan is common in the Highlands of Scotland today, either as a forest limit or forest fringe species (where isolated stands of pine or birch forest occur), or associated with light pine or birch woodland, then it would not be surprising to discover that it was an important component in the developing early Flandrian vegetation. Significant percentages of Sorbus pollen grains are recorded in the Betula-Corylus zone (Mod, Fig. 24) at Mollands. In addition to juniper, willows and aspen, rowan may have been locally interspersed with birch and hazel in the early Flandrian succession stages in southern Perthshire. Thus the apparent absence of Populus, Sorbus and Juniperus from parts of the early Flandrian pollen records in some of the sites from southern Perthshire may be misleading. At those sites where particularly thick stands of birch, hazel and willow surrounded the lake waters or developing mire, pollen of other genera may not have been able to filter through to be deposited on the lake or mire surface. If the factors of over-representation of birch and hazel and of destruction of Populus exines are also considered, then it can be seen that it would be dangerous to argue on the basis of the absence of records of certain genera.

Of particular note in the Betula-Corylus zone is the subdivision in the lower part of the zone at Glenturret. Sub-zones Gla I, Gla II and Gla III have been identified here (Fig. 26). Pollen percentages of Corylus characteristically and dramatically fluctuate in Flandrian pollen diagrams from the British Isles (Godwin, 1956), and this is also exhibited in the pollen diagrams from southern Perthshire. However, at the base of zone Gla there is a marked decrease and re-increase in Corylus pollen percentages that form a somewhat less erratic fluctuation than is usual in the Corylus frequency curves. The initial decrease in Corylus percentages from a value in excess of 90% to a value of 20% AP is consistent over 5 spectra, and the subsequent increase from 20% to values in excess of 90% AP is also consistent over a further four spectra. In contrast to other Corylus frequency fluctuations this decline in the representation of Corylus in sub-zone Gla II is regarded as significant, and is interpreted as indicating a temporary set-back in the successful immigration of hazel at Glenturret.

The reason for this phenomenon is not known. It is possible that it could indicate a change in vegetation composition that resulted from some change in climatic conditions. For instance, Corylus avellana is a more warmth demanding species than Betula pubescens (Godwin, 1956), and a critical factor is the incidence of spring frosts, for C. avellana flowers very early and the stigmas of the flowers are sensitive to frost (Godwin, 1975). The dominance of Betula over Corylus in sub-zone Gla II could indicate reduction in the flowering of Corylus during a period in which spring frosts were critical for Corylus but not for Betula. However, similar fluctuations in pollen frequencies are not recorded at the other sites. It might be argued that critical climatic thresholds were crossed at an upland site, such as Glenturret, but not at lower sites, but a comparable oscillation in the Corylus curve does not occur in the diagram for the upland site of Amulree. Further, no evidence has yet been reported from Scotland that supports this interpretation (see chapter 12). Thus until more sites have been investigated to determine whether or not this oscillation at Glenturret was a local anomaly, the subdivision of the Betula-Corylus zone remains tentative and without adequate explanation. Despite the consistent percentage changes, this oscillation may nevertheless relate to chance dispersal of pollen from a regional source.

There are no dates available for the major expansion of Corylus in southern Perthshire, but three dates relate to the first significant appearance of Corylus at three sites. This is dated to 9,365 ± 120 B.P. at Mollands, 9,260 ± 100 B.P. at Tynaspirit, and 9,115 ± 120 B.P. at Amulree. Taken together these dates indicate that the establishment of hazel was more or less synchronous throughout southern Perthshire. This in turn indicates rapid immigration and spread of hazel in view of the altitudinal and latitudinal differences between Amulree and the Teith Valley sites.

4. THE ESTABLISHMENT OF CLOSED MIXED FOREST

A common feature of the Flandrian diagrams, though rather differently expressed in each diagram, is a major increase in arboreal pollen following the dominant Betula-Corylus phase. Pinus, Ulmus, Quercus and Alnus immigrated into southern Perthshire during the Betula-Corylus phase, and the eventual development of a closed forest canopy is indicated by the marked reduction in pollen of the more light-demanding species. Thus the reduction of Corylus pollen percentages coincident with the expansion of arboreal pollen percentages is one of the most marked features in each diagram (zone Mof, Fig. 24; Cli, Fig. 19; Tlh, Fig. 16; Amli, Fig. 21; Glb/c, Fig. 26). Pollen of Juniperus, Populus and Sorbus (where relevant) virtually disappear. Salix is the only shrub to be well represented in the pollen diagrams, but this is probably related to extremely local growth of willow at each site (see section 6). Betula pollen percentages consistently decline following the close of the Betula-Corylus phase as the totals for other forest elements gradually increase.

There is little doubt that mixed forest covered large areas of southern Perthshire during a major part of the Flandrian. No dates are available from southern Perthshire, but on the basis of radiocarbon dates from other regions mixed forest may have dominated the landscape of large areas of southern and central Scotland by about 7,500 B.P. or even earlier (see chapter 12). Even in the upland sites of Glenturret and Amulree shrubs are markedly reduced in the pollen diagrams following the Betula-

Corylus phase, but here Betula continues to dominate the arboreal components, in contrast to the diagrams from the Teith Valley.

Before a general comparison of the pollen diagrams can be attempted, it is necessary to discuss the role of the different arboreal genera separately, for there are a number of complications in the diagrams. Only Pinus, Ulmus, Quercus and Alnus are considered as the scant or isolated records of Fraxinus and Tilia are thought to represent long-distance transfer of pollen and not the presence of these trees within southern Perthshire.

Pinus

Pollen of Pinus is continually recorded throughout each diagram, and where the percentages are consistently lower than 5% this probably reflects the transfer of pollen grains from stands of pine established outside the region. Vasari and Vasari (1968) claim that consistent records of 10% are required to indicate the regional growth of pine trees. In the pollen records from southern Perthshire this is achieved only at the end of the Betula-Corylus phase at three sites, Glenturret, Amulree and Mollands. At these three sites percentages of between 10 and 20% are recorded, but the strongest representation is in the Mollands diagram where a number of spectra record percentages in excess of 30%.

The interpretation of Pinus pollen percentages or macrofossil records is difficult, for the growth of Pinus sylvestris can have a number of ecological interpretations. In most situations Pinus cannot compete with broad-leaved forest trees, though it can become established within deciduous forest where altitude, exposure or poor acidic soils limit the growth of other forest components (Godwin, 1975). In the Highlands of Scotland today pine is naturally associated with podsolic soils (Steven and Carlise, 1959; McVean and Ratcliffe, 1962), and it is possible that pine only became established in certain regions once the process of leaching had resulted in a substrate on which pine could compete more strongly. Such a process would, of course, have required a variable amount of time depending on the relative base-status of different localities. The growth of Pinus is also sometimes commonly associated with fens and with the transition from fen to raised bog in vegetational successions. Further, pine is commonly associated with the drier margins of peat bogs (Pennington, 1969) or the surface of blanket bogs when climate in the past was relatively dry (Birks, 1975).

Pine may have been a widespread component in the regional vegetation of southern Perthshire, though it was by no means a dominant component as at sites north of the Highland watershed (Pears, 1968; H.H. Birks, 1970; O'Sullivan, 1974; Walker, 1975b). It may have been locally more important on steeper and higher slopes. However, a notable feature in the diagrams for Glenturret and Mollands is that the major Pinus expansion occurs where there is a major increase in percentages of fern spores, where aquatic pollen disappear from the diagram, and where taxa possibly indicating fen conditions, such as Alnus and Salix, increase markedly in the diagram. The sharply fluctuating percentages of Salix and Alnus at Mollands (Fig. 24) suggest over-representation of locally-growing species. The diagram for this latter site should be contrasted with that of Cambusbeg (Fig. 19). Here no Pinus phase is recorded, and open-water conditions prevailed.

The evidence thus suggests that the increase in Pinus pollen percentages indicates, at least in part, the local growth of pine that was able to colonise a drying bog surface. This would seem to have occurred at Mollands and Glenturret. If Pinus had been a major regional forest component in the Teith Valley, which is the alternative explanation for the relatively high values of Pinus pollen at Mollands, then it would be difficult to explain why this is not reflected in the Cambusbeg pollen diagram.

Ulmus and Quercus

Ulmus and Quercus are represented with higher pollen percentages in the diagrams from southern Perthshire than they are in most other Scottish pollen diagrams. Percentages for these two genera are not as high but are comparable with the relatively high percentages recorded for sites in south-east Scotland by Newey (1968). The development of mixed deciduous woodland thus seems characteristic of at least the eastern part of the Midland Valley, and the evidence from Glenturret and Amulree suggests that mixed deciduous woodland encroached onto the Highland edge along major south-facing valleys. The stronger representation of Ulmus and Quercus in south-east Scotland is attributed by Newey to the more favourable climatic and edaphic conditions in this area. The higher representations of these two genera in the diagrams from the Teith Valley as compared with Glenturret and Amulree thus probably reflect the more sheltered conditions and deeper soils of the lowland valley. Also in agreement with Newey's findings is the relatively greater importance of Quercus over Ulmus for sites in the Teith Valley. This is especially reflected in the Cambusbeg diagram. However, in the upland sites of Amulree and Glenturret, elm was apparently more important than oak, as is indicated by the significantly higher percentages of Ulmus pollen. This is especially marked at Amulree, and if corrosion of Quercus pollen grains can be discounted as the prime cause of this relationship, then it would appear that the more demanding Ulmus was better established than oak at the upland sites (see below).

The Ulmus pollen almost certainly represent the local presence of the Wych elm, U. glabra. Ulmus and Quercus pollen are generally under-represented in pollen diagrams, and values of consistently between 5-10% or more of Ulmus pollen are generally regarded as indicating the presence of elm in the regional vegetation. Quercus pollen can be especially under-represented in a pollen diagram, for Quercus is a genus of low pollen productivity and the pollen exines are rather susceptible to corrosion (Godwin, 1975). Today two species of Quercus are common in the British Isles, Q. robur and Q. petraea. The former predominates on heavy clay soils and loam soils, though it is sometimes co-dominant with Q. petraea on damper acid soils. Q. petraea is characteristically dominant on siliceous soils. Both species may be represented in the pollen diagrams, but it is likely that the more frequent species would have been _Q. petraea_ (Tansley, 1949; Clapham _et al_., 1962; Perring and Walters, 1962).

In general _Ulmus_ and _Quercus_ immigrated at about the same time in southern Perthshire, but _Ulmus_ may have been able to establish itself more quickly than oak. Thus _Ulmus_ percentages usually expand earlier than those of _Quercus_. This may explain why _Ulmus_ pollen percentages are higher than those of _Quercus_ at Amulree and Glenturret. Thus while climatic and edaphic conditions were suitable for elm and oak, they would have spread throughout the region. If, however, climatic or edaphic deterioration later set in (see below) then this may have occurred before oak had established itself fully within the valleys of Glenturret and upper Glen Almond. Though oak appears to be the dominant deciduous tree for the region at the time of maximum forest development, the time factor may have prevented the natural plant succession from progressing towards a natural climax in some valleys along the Highland edge. However, other evidence is not in keeping with this hypothesis (chapter 12). This feature therefore remains problematic.

Thus there is variation in the development of deciduous woodland between these sites. This is also reflected in the differential representation of the Elm Decline, which is discussed below.

Alnus

A major expansion of alder is recorded at three of the sites, _viz_. Mollands (Fig. 24), Cambusbeg (Fig. 19), and Glenturret (Fig. 26). The marked increases in _Alnus_ pollen percentages at the Mof/Mog, Cli/Clj, and Glc/Gld boundaries, and their continued high percentages in the diagrams thereafter, suggest that a major expansion of alder trees took place within the general forest cover of southern Perthshire. The _Alnus_ pollen records from southern Perthshire can safely be attributed to _A. glutinosa_, for in the British Isles sub-fossil remains of _Alnus_ in the Flandrian usually belong to this species (Godwin, 1975). The macrofossil records of _Alnus_ in Aberdeenshire, for instance, are all of A. glutinosa (Vasari and Vasari, 1968).

The high percentages of alder pollen must, however, be considered with caution for two principal reasons. Firstly, A. glutinosa begins to flower at a very early age and has an extremely high pollen productivity. Alnus pollen grains are therefore greatly over-represented in pollen diagrams (Andersen, 1970, 1973). Secondly, alder is a common component of fen vegetation, usually associated with mesotrophic mires, and thus can be over-represented in a pollen diagram as a result of its growth immediately around or on the mire surface.

It might therefore seem questionable that high percentages of alder pollen reflect a major change in regional vegetation. However, the evidence for widespread expansion of alder throughout the British Isles is overwhelming, and it is generally assumed that this widespread expansion is related to a significant change to more oceanic climatic conditions (Godwin, 1975). The Alnus rise in Flandrian pollen diagrams is not synchronous throughout the British Isles (see chapter 12), but it is assumed here firstly, that the marked increases in Alnus pollen at the three horizons named above reflect regional as well as local expansion of alder, and secondly, that the regional alder expansion was more or less synchronous within the confines of southern Perthshire.

From the pollen evidence it appears that the regional expansion of alder was very rapid. This could have occurred only with alder already well established within the region. The Mollands diagram (Fig. 24) indicates that alder fen and carr had developed around the margins of this site some time before the major regional expansion of alder. Fluctuating percentages of Alnus are recorded in zones Moe and Mof, though the first significant records are in Mod, and these relatively high percentages are associated with fluctuating percentages of Salix and Cyperaceae, and with other pollen grains or spores indicating the development of fen vegetation (see section 6). Fen vegetation is also probably represented in zones

Glc and Gld at Glenturret (section 6). Fen vegetation is not clearly represented in the Cambusbeg diagram (Fig. 19), for this site continued to contain open water throughout most of the Flandrian. However, the isolated peaks of Alnus pollen in zones Clh and Cli may be related to the growth of alder around the margins of the site.

In addition to growth on mires, alder was also likely to have been established along stream and river courses, as it is in the Scottish Highlands today (McVean, 1953). How early in the Flandrian alder immigrated into southern Perthshire is difficult to establish, though in locally favourable sites this may have been as early as the beginning of the birch-hazel phase. Thus percentages of up to 10% AP of Alnus pollen are recorded in the earlier part of the birch-hazel phase at Mollands and at Cambusbeg. This suggests that temperatures in southern Perthshire were suitable for the establishment of alder for much of the Flandrian, and since the major expansion of alder occurred relatively late in the Flandrian then the genus must have been restricted previously to waterside and fen localities by competition from other trees. The rapid expansion of alder in southern Perthshire thus agrees with the conclusions of Pennington et al. (1972) that a change in general climatic conditions had resulted in a rise in water tables which in turn had resulted in the widespread development of moist habitats suitable for the establishment of alder seedlings.

A contrast is evident between the lowland sites of Mollands and Cambusbeg and the upland site, Glenturret. In the former, Alnus pollen percentages dominate the arboreal pollen components following the main alder rise. In the latter site birch continued to be the dominant tree component, though alder was second in importance. This may reflect the fact that alder is relatively warmth-demanding, the most important factor being the sensitivity of seedlings of alder to late spring frosts (McVean, 1953). Alder is also relatively sensitive to wind exposure, and the probable greater incidence of severe frosts and strong winds at the higher site may have limited the expansion of alder there. However, the difference between the representation of alder between upland and lowland sites may also be related to the effects of Man (see below).

In conclusion to section 4 it is apparent that in the Flandrian a mixture of oakwood, and birchwood, with elm also important, was the dominant vegetation throughout southern Perthshire prior to the main alder rise. It is difficult to establish the density of the forest cover, since trees in general, and birch especially, are generally grossly over-represented in pollen diagrams in comparison to many non-arboreal taxa. _Pinus_ and _Alnus_ were generally restricted in southern Perthshire at that time, _Alnus_ due to relatively dry climatic conditions, and _Pinus_ due to edaphic conditions. Both alder and pine could not compete with the well established oak-elm-birch forest prior to the main alder rise.

5. THE ELM DECLINE AND REGENERATION OF BIRCH AND HAZEL

The Elm Decline is a well known feature in north-west European pollen diagrams, though in most sites from northern Britain it is not clearly marked (Pennington _et al._, 1972; O'Sullivan, 1974). According to Hibbert _et al_. (1971) and Smith and Pilcher (1973) this event was broadly synchronous throughout the British Isles and even in north-west Europe as a whole. Initially it was believed that the Elm Decline had a climatic cause (Godwin, 1956), though anthropogenic factors were also thought to contribute to the sudden decline of elm. Presently three possible causes are suggested, and there are arguments for and against each of these having been the prime cause of the Elm Decline: these are climatic change, anthropogenic effects, and elm disease (Godwin, 1975). Anthropogenic control is favoured by a number of palynologists, and the Late Flandrian sub-stage, defined as the period when anthropogenic disturbance of natural vegetation becomes important, is regarded as commencing at the Elm Decline (West, 1970).

At Mollands the Elm Decline is very clearly marked (Fig. 24). It coincides with the virtual disappearance of pine, reduction in percentages of Quercus pollen, and marked increases in Betula and Corylus pollen percentages. If anthropogenic control is advanced as explaining the clear decline in elm pollen frequencies at this site then this control was likely to have been very limited, for arboreal pollen continue to be very important in the diagram. Thus Fig. 24 suggests significant changes in forest density and composition, but not widespread and continuous clearance of forest. Forest clearance appears to have been selective, for elm virtually disappeared from this site, while oak, though reduced, continued to be relatively important.

Expansion of birch and hazel, and to a certain extent alder, is consistent with the view that forest clearance occurred following the Mog/Moh pollen zone boundary (Fig. 24). Birch regeneration is a familiar sight in the Scottish Highlands today, for it regenerates more freely than any of the other native trees of Scotland as a result of prolific seeding and good powers of dispersal (McVean and Ratcliffe, 1962). Hazel also regenerates freely, and has the added advantage that its foliage is unpalatable to cattle. Thus increased percentages of hazel pollen have been found to occur in association with Late Bronze Age and Early Iron Age clearances at Tregaron in central Wales, and these have been interpreted as indicating under-grazing of partly cleared woodland (Turner, 1964, 1965). The slightly increased representation of Alnus at Mollands following the Elm Decline is interpreted as indicating the preferential clearance of elm and oak from the drier and more favourable localities, whilst alder, established on the wetter stations, was left relatively untouched. Under such conditions alder would maintain and (as at Mollands) even increase its representation in a relative frequency pollen diagram.

Only a slight reduction in elm pollen percentages is represented in the Glenturret pollen diagram (Fig. 26), though regeneration of birch and hazel is evident in zone Gle. Thus anthropogenic interference did not affect the vegetation at this upland site as markedly as at Mollands. An interesting point to note from the Glenturret diagram is the continued importance of elm and oak following the regeneration of birch and hazel. If the birch-hazel regeneration phase at Glenturret is synchronous with that of Mollands, then this suggests that the Elm Decline as recorded at Mollands was not caused primarily by climatic deterioration, for this should then have been more strongly reflected at Glenturret. The Elm Decline is poorly represented at Cambusbeg (Fig. 19), for pollen percentages of elm are lower at this site than at Mollands. The marked increase in hazel pollen frequencies at the top of zone Clj indicates that the base of the birch-hazel regeneration phase occurs at the top of this diagram.

Pollen grains of taxa indicative of Neolithic farming have been found following the Elm Decline in some pollen diagrams. These include pollen of Plantago lanceolata, Urtica dioica, certain grasses, and some Compositae (Pennington, 1969). Significant percentages of Urtica dioica are recorded in zone Clj (Fig. 19) and of Plantago (undifferentiated) in zones Mog and Moh (Fig. 24). Whether these records indicate settled Neolithic farming at such an early time in this part of Scotland is difficult to say from the evidence in this thesis alone. Durno (1965) has interpreted fluctuations of Pteridium, Calluna, and Gramineae as also indicating forest clearance by man. It is noted that percentages of Ericaceae and Gramineae increase in the Mollands diagram following the Elm Decline, but whether these increases can be attributed to Calluna and species of Gramineae indicative of human clearance is not known. Grass species indicative of oligotrophic conditions and associated with the development of ombrogenous peat (see below) are probably represented in this part of the diagram. Taking the evidence as a whole, however, it would appear that forest clearance was effected by Neolithic man in southern Perthshire, and that this was more important in the main lowland valleys, such as the Teith, than in upland localities. The continued importance of arboreal pollen percentages following the Elm Decline, and the regeneration of hazel, suggest either that the forest was in general only partly cleared or that forest clearance was extremely selective.

6. HYDROSERAL SUCCESSION IN THE FLANDRIAN

(i) Mollands (Fig. 24).

A well defined hydroseral succession is reflected in the mire stratigraphy and pollen spectra at Mollands. This is best considered in three broad but not mutually exclusive (in terms of historical development over the mire as a whole) stages: the mainly aquatic stage (zones Moa-Mod - see also Fig. 25), the gradual development of fen communities (zones Mod to Mog), and the development of ombrogenous peat (zone Moh).

In zones Moa to Mod pollen of obligate aquatic taxa are strongly represented, especially of *Potamogeton* and *Myriophyllum*. The aquatic pollen percentages are highest in zone Mod, which probably indicate shallower lake waters that permitted the expansion of pondweeds (*Potamogeton*) and water-milfoil (*Myriophyllum*). Water was initially too deep in zones Moa-Moc in large parts of the basin, which restricted the growth of rhizomes of pondweed and water-milfoil until a suitable accumulation of lake muds had been achieved. The bur-reeds are also strongly represented in zone Mod. These can either indicate reed swamp or shallow water conditions, but the marked increase in percentages of *Equisetum* spores in zone Mod indicates that much of the basin had probably been infilled at this time. The *Equisetum* spores probably represent the invasion of water horsetails (*E. fluviatile*) and marsh horsetails (*E. palustre*) which require shallow water or marsh conditions.

Pollen of Gramineae and Cyperaceae increase gradually throughout zone Mod and are recorded at exceedingly high frequencies at the Mod/Moe transition. This reflects the development of reed swamp at Mollands, probably involving reed mace (*Typha angustifolia*), species of *Carex*, and common grasses may have included the reed Phragmites communis, reed sweet grass (Glyceria maxima) and floating sweet grass (Glyceria fluitans). A similar pattern to the curves of Gramineae and Cyperaceae is followed by the spores of Filicales. They too expand dramatically at the Mod/Moe pollen zone boundary following a more gradual increase throughout zone Mod. The term 'Filicales' embraces a number of families of the order Pteridophyta, and these in turn include a large number of genera that together cover a wide ecological spectrum (Clapham et al., 1962). It is not possible to separate those spores indicating taxa of marsh or fen conditions from those commonly associated with woods such as the male fern (Dryopteris filix-mas). The latter could only be recognised where the perine had not been detached from the spore.

Following the development of sedge fen communities in zone Mod, natural succession at Mollands led to the invasion of the mire surface by Salix and Alnus. This usually follows the development of sedge fen at or just above water-level, and the growth of sallow (Salix atrocinerea) and alder carr (Alnus glutinosa) usually indicates a drying mire surface. Commonly associated with willows and alder at this succession stage are birch trees, and Betula pubescens is found on the mire surfaces of Cambusbeg and Tynaspirit today, but not at Mollands. Pine can also invade the drying mire surface, as also appears to have occurred at Mollands during zone Mof. With the development of such fen communities, including species that liberate immense quantities of pollen, the regional terrestrial communities must be greatly under-represented in zones Moe-Mog.

The significant increase in Sphagnum spores in zone Moh indicates the development of ombrogenous peat. The increased percentages of Gramineae and Cyperaceae associated with this Sphagnum phase probably represent the growth of oligotrophic species commonly associated with Sphagnum bogs, such as cotton grass (Eriophorum vaginatum) and purple moor grass (Molinia caerulea). The increased percentages of Ericaceae pollen in this zone are also consistent with the concept of the development of a 'regeneration complex' at this time (Godwin, 1975), with ericaceous plants invading the drier hummocks of the developing Sphagnum bog.

The scheme outlined above is a simplified interpretation of the pollen spectra, for it is understood that different stages of the hydroseral succession would have been experienced at the same time in different parts of the basin. Thus in zones Moa-Mod, whilst the centre of the basin would have contained relatively deep water, the edges of the basin would have already progressed to reed swamp and sedge fen stages. The edge of the mire may have been invaded by willows at a very early stage, for percentages of between 10% and 20% Salix pollen are recorded from the beginning of zone Mod. Conversely, the continued representation of pollen of obligate aquatic plants indicates the presence of pools of open water until the close of zone Mof. In addition there is the possibility that major changes in the level of the water table may have occurred during the Flandrian, as is possibly indicated by the marked peaks in pollen of Potamogeton and spores of Equisetum in zone Mod.

Despite these complications, three horizons are thought to indicate important developments of the Mollands mire. First, the Mod/Moe boundary probably indicates the time when much of the basin was infilled, and only isolated pools of water remained in the deeper parts. Secondly, the Mof/Mog boundary probably indicates the time when the basin was completely infilled, and, despite the indication of a change to more oceanic climatic conditions by the alder rise, the mire surface was relatively dry. Thirdly, the Mog/Moh boundary coincides with the change to ombrogenous peat development.

The Mod/Moe pollen zone boundary also roughly coincides with a change in mire stratigraphy from highly humified peat to fine-detritus peat, initially with wood fragments (lithostratigraphic unit 4) and with remains of Sphagnum leaves throughout. The wood fragments were badly decomposed and were thus not identified. The reason for the absence of significant records of Sphagnum spores in lithostratigraphic units 4 and 5, where macrofossils of Sphagnum have been noted, is not readily understood, though it has been suggested in chapter 6 that Sphagnum spores may be susceptible to chemical alteration processes. The relationship of the variation in the number and type of deteriorated pollen grains to local vegetational succession at Mollands has also been covered in chapter 6.

(ii) Glenturret (Fig. 26)

A similar reflection of hydroseral succession to that at Mollands is contained within the Glenturret pollen diagram, though at this site there is less taxonomic detail. The main aquatic phase is represented in zones Gla and Glb, though the transition from open water to reed swamp and sedge fen communities was largely completed during pollen zone Glb. As the curve for aquatic pollen reveals, this site continued to contain pools of open water throughout the period represented by Fig. 26. During zones Glc and Gld alder and willow invaded the bog surface, and pine may also have encroached onto the edge of the mire, though the growth of pine appears to have been short-lived at Glenturret.

A problem exists in the recognition of the main alder rise at Glenturret. It is presumed that the consistently high percentages of pollen of alder following the Glc/Gld boundary indicate that that biostratigraphic horizon represents the main alder rise at this site. However, the pollen spectra as a whole indicate that at about pollen zone Glc fen communities became dominant in the Glenturret basin, and this may also have involved alder carr. Thus difficulty can arise when employing the 'alder rise' as a basis for correlation between pollen diagrams (chapter 12).

Towards the end of zone Glb the basin was largely infilled. This is indicated by the pollen spectra and by the change from humified peat (lithostratigraphic unit 3) to peat with Sphagnum remains indicating the development of ombrogenous peat. The transition to lithostratigraphic unit 5, where there is a return to the deposition of humified peat, indicates that water levels in the basin had risen and ombrogenous peat development was more restricted. This is therefore consistent with the concept that there was an overall change to more oceanic climatic conditions, as indicated by the expansion of alder in zones Glc-Gle. As at Mollands, relatively small percentages of Sphagnum spores are recorded in the upper parts of zone Glb and in zones Glc and Gld, despite the deposition of Sphagnum macrofossils.

(iii) Tynaspirit (Fig. 16)

The Tynaspirit diagram records only a short part of Flandrian vegetational history, being restricted mainly to the birch-hazel phase. Aquatic pollen are well represented throughout the diagram, indicating open water conditions until after the Corylus decline. The increase in Pteridophyte spores and in pollen percentages of Gramineae, Cyperaceae, other herbs and Salix in zone Tlh reflects the development of reed swamp and fen around the edge of the basin.

(iv) Amulree (Fig. 21)

Mire development at this site contrasts with those of the three sites previously discussed. At about the Amlg/Amlh pollen zone boundary, i.e. at about the time of the main Corylus decline, aquatic pollen percentages decline markedly and herbaceous pollen, especially Cyperaceae, and spores of ferns and Sphagnum moss significantly increase. There is also a sharp and important change in lithostratigraphy at this boundary, from humified peat (lithostratigraphic unit 10) to mainly Sphagnum peat (lithostratigraphic unit 11). The macrofossil remains identified in lithostratigraphic unit 11 are described in more detail in chapter 2, but the main plants identified were Sphagnum, Eriophorum, Carex, Menyanthes, and in the upper part of the unit ericoid stems and Scirpus remains.

The evidence suggests that water tables were lowered at the time of the Amlg/Amlh boundary, and a regeneration complex peat growth (Walker and Walker, 1961) was established at Amulree. Regeneration complex peat consists of a mosaic pattern of hummocks and hollows, where the hummocks are formed by the bog moss Sphagnum, with ericoid species and Eriophorum on the drier crests of the hummocks, and these are separated by pools of water wherein more hydrophilic species, such as species of Carex, Scirpus and Menyanthes, are to be found. Regeneration peat can develop above the water table since water can be carried upwards within the mire as a result of capillarity. Thus this type of peat is often associated with domed mires.

At present the surface of the bog at Amulree is strongly domed, with a lagg containing standing water around the perimeter. The surface is broken into numerous hummocks and hollows, and ericoid species are dominant on the hummocks. Thus the growth of the domed mire has progressed since the time of the main Corylus decline. However, the history of the bog cannot be determined from the details in a single core (Fig. 21) and from the pollen spectra alone. Theories on the growth of regeneration complex peat are confusing (Moore and Bellamy, 1974), even where full stratigraphic details across a mire complex are available. The records of Sparganium and Nuphar towards the top of zone Amlm suggest that large pools of water may have survived throughout the Flandrian at Amulree that are not well represented in the pollen spectra abstracted from this particular core. The appearance of Sparganium and Nuphar may also be related to markedly higher water tables that resulted from climatic change. It is noted that Alnus also increases sharply at the top of zone Amlm, and since fen communities are not strongly represented at this site this increase in pollen percentages may relate to the regional expansion of alder.

(v) Cambusbeg (Fig. 19)

The Flandrian sediments at Cambusbeg consist of an extremely soft, homogeneous organic mud which is watery in nature between 870 and 950 cm and gel-like between 950 and 1070 cm. Such gel-like soft organic mud has been termed dy by Faegri and Iversen (1964). Between 150 and 870 cm an extremely watery organic mud, or in some places only water, is enclosed by a floating mat of mire vegetation supporting a number of birch trees (see chapter 5, section 2). This mire thus corresponds to the "schwingmoor" (Moore and Bellamy, 1974).

The pollen spectra indicate open water conditions throughout pollen zones Clf to Clj, but the fluctuating percentages of pollen of Gramineae, Cyperaceae, Alnus, Salix, and Filipendula (particularly in zones Clh and Cli) and of Filicales spores, indicate marginal fen and marsh. It is not possible to determine the history of the growth of the surface mat of vegetation from the evidence available, except to note that a complete surface mat of vegetation must post-date zone Clj since floating-leaved macrophytes are still represented at this stage.

(vi) Synthesis

If the local mire developments, as indicated by pollen spectra and lithostratigraphy, are compared schematically (Fig. 36) a number of conclusions can be drawn. For the purposes of simplicity in Fig. 36 it has been assumed that the Corylus rise, Corylus decline, and main Alnus rise are synchronous within southern Perthshire. These have been discussed in detail earlier in this chapter, and their chronology is discussed in chapter 12. As described above, the pollen diagrams have been interpreted in a very general way for the purposes of this diagram, with the recognition of pollen spectra indicating broadly communities of aquatic macrophytes, marsh conditions, fen conditions, ombrogenous peat (unspecified) and regeneration complex peat. It is realised that a number of the taxa recognised in each diagram can be associated with several ecological divisions, however, Fig. 36 is not intended to be precise but is used merely to illustrate a number of general points. In the figure broken lines indicate that the communities are not strongly represented in the pollen diagrams, and solid lines that they are well represented.

One major point to note is that mire development was not necessarily controlled by regional changes in environmental conditions. Thus although

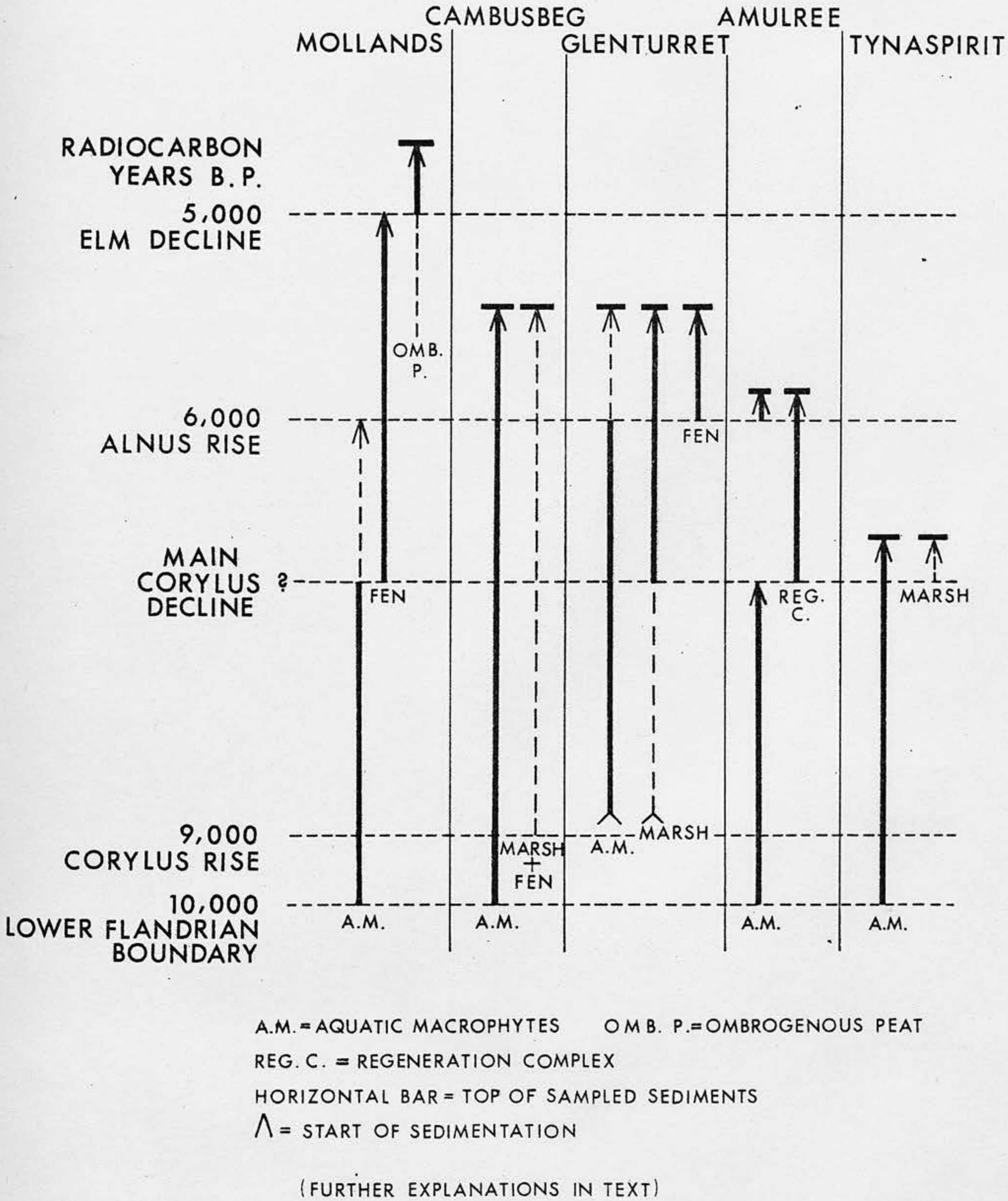


FIGURE 36 A generalised outline of mire development during the Flandrian at sites in southern Perthshire.

the regional climatic wetness marked by the alder rise appears to have caused higher water tables at Amulree and possibly also initiated the development of ombrogenous peat at Mollands, the mire at Glenturret continued to progress in a natural hydrosere succession from aquatic macrophytes through reed swamp and marsh conditions to fen. In fact the main transition to fen, indicating a mire surface at or above the local water table, took place at the time of the alder rise. This reflects the fact that Glenturret basin peat deposits accumulated following the development of a perched water table (see chapter 5, section 4). Thus mire stratigraphy was related mainly to local conditions affecting the water table, and not to regional climatic changes.

However, at the two sites at which the alder rise appears to have been important, mire stratigraphy also bears a relationship to the Corylus decline. Thus at Amulree regeneration complex peat began to develop at this time, and the change from open water to fen conditions largely took place at this boundary at Mollands. The relationship of mire stratigraphy and plant community changes to two boundaries indicating regional environmental changes at each of these two sites suggests that in both basins mire development was primarily related to regional environmental changes.

Mire development is also closely related to geochemical factors at any particular site. Base-status within a basin is related to the nature of the local rock and drift, and in a historical context to changing conditions affecting erosion and leaching. At Glenturret, Mollands and Tynaspirit (though at this latter site only the earlier part of the Flandrian is represented) base-status appears to have been maintained at a relatively high level throughout the time periods represented, since fen communities developed strongly at each of these sites. Fen communities gave way to the development of ombrogenous peat at Mollands following the Elm Decline.

The mires at Amulree and Cambusbeg have developed in conditions of low nutrient input. At Amulree leaching on surrounding slopes may have been much quicker than in other catchments. This would have led to acid drainage waters which in turn would have promoted the development of Sphagnum bog within the basin and at the basin-edge. The sediments at Cambusbeg indicate exceedingly dystrophic conditions (Moore and Bellamy, 1974). Under conditions of exceedingly low nutrient input productivity within a basin is very low, and instead of the more normal colonisation by reed swamp communities a floating mat of acid tolerant plants gradually spreads across the surface of the water ponded in the basin.

Finally mention should be made of the likelihood that some of the pollen records of herbaceous plants are related not only to local hydroseral developments but also to the herb layer beneath the surrounding woodland. With the invasion of juniper and Empetrum heath at the beginning of the Flandrian, followed by the development of birch-hazel woodland, the herbaceous flora became suppressed and many species disappeared in this region. However, the continued significant representations of Gramineae and Cyperaceae, and of other herbaceous taxa throughout the mid-Flandrian forest period may indicate the existence of tracts of open grassland within the forest cover, especially on steeper and higher slopes. Some of the pollen and spores, e.g. species of Umbelliferae, Lycopodium and Dryopteris, may reflect the ground herb layer beneath woodland. Pollen of Filipendula and Ranunculaceae, however, probably derived from plants of a local marsh community at the margins of the lake. Without species identifications it is not possible to be more precise in interpreting the herbaceous pollen and spore assemblages.

7. CONCLUSIONS

Without chronostratigraphic data correlation between pollen diagrams on the basis of major arboreal changes in the Flandrian can be misleading. Several clearly marked horizons in the Flandrian pollen diagrams from southern Perthshire have been interpreted as indicating regional vegetational changes, and these have been assumed to be more or less synchronous within the confines of southern Perthshire. At least one of these horizons, the alder rise, is however difficult to delimit in some diagrams since alder may have been associated with local fen development. In the same way, birch carr may also have developed at some sites, and pine may have invaded the drier margins of mires during the Flandrian. These arboreal genera can thus be greatly over-represented in the pollen diagrams, and it is difficult to separate pollen fluctuations indicating widespread regional changes from those indicating local changes only.

Nevertheless, the following main horizons are clearly recognised in most if not all of the sites, and are regarded as synchronous: the expansion of juniper heath (chapter 8); the immigration and expansion of birch woodland; the development of birch-hazel woodland; the main alder rise. In addition an important horizon, the Elm Decline, is positively represented at at least one site (Mollands).

Prior to the major expansion of alder, which is interpreted as indicating a major climatic change from relatively dry to more oceanic conditions, the maximum forest development in the Teith Valley during the Flandrian was of a mixed oak-elm-birch forest, which was locally dense and probably dominated by oak. In the upland sites forest continued to be dominated by birch and was much lighter. In such areas elm was probably more important than oak in the local flora, and this may have been related to the inability of oak to establish dominance throughout southern Perthshire as a whole before the climatic deterioration marked by the alder rise. This interpretation depends, however, on climatic and edaphic inferences which are reserved till chapter 12. Pine was established only extremely locally in southern Perthshire at all times during the Flandrian. The marked differences in the representation of pine between sites in the Teith Valley suggests that the development of pine was extremely sporadic, perhaps related to poorer soils or to mire surfaces. Pine appears to have been virtually absent from the area around Amulree throughout those parts of the Flandrian that are recorded. A number of important species are probably greatly under-represented in the pollen diagrams, including rowan, aspen, and, in the later parts of the Flandrian, juniper.

The interpretation of mire stratigraphy is extremely complicated, but from the evidence presented here there appear to be major differences evident between the sites that are related to the relative importance of regional or local factors governing water tables, and to the relative base-status of local substrates and drainage waters within the catchments.

CHAPTER 12

Chronology of events in the Flandrian and ecological inferences based on a comparison of the palynological data from southern Perthshire with other published data

1. INTRODUCTION

It is possible to place the generalised scheme of Flandrian pollen zones described in chapter 11 into a perspective of absolute time since the major horizons recognised have parallels in many parts of the British Isles. Some major biostratigraphical horizons cannot everywhere be synchronous, as time is required for the natural immigration of forest species, and metachronism is greatest at those localities farthest from the refugia of Lateglacial times. It is therefore necessary to interpolate from often widespread information. The task is made more difficult by the relative scarcity of dates from middle and late Flandrian vegetational sequences from eastern districts of the Midland Valley of Scotland. This is surprising in view of the evidence presented by Durno (1956), Donner (1957), Newey (1965, 1966) and Brooks (1976), which is to some extent corroborated by evidence presented in this thesis, that the forest phases used by Godwin (1956) as zonal criteria for the subdivision of pollen diagrams are clearly recognisable in pollen diagrams from the eastern districts of the Midland Valley. Radiocarbon-dating of samples abstracted from the precise horizons indicating major changes in forest composition would provide a direct comparison of forest history between eastern Scotland and south-east England and might clarify chronological relationships.

It should be pointed out that in one site in particular, namely Mollands, a number of basic similarities can be found in a comparison of the Flandrian pollen zonation with that of Godwin's zonation scheme described for Hockham Mere (1940). The similarity in the successional phases involving Betula, Corylus, Ulmus, Quercus and Alnus is remarkable. However, the detailed criteria employed by Godwin in his overall subdivision, especially in the expansion and exclusion of Pinus, is markedly dissimilar in the Mollands diagram. Further, as reviewed in chapter 11, a number of inconsistencies are evident in comparing the successions at different sites in southern Perthshire. The diagram from Mollands may represent a succession from sites situated in the most favourable locations (in terms of climate and edaphic conditions) which also contain relatively eutrophic lake water. Under such circumstances vegetational succession may have paralleled that experienced in parts of England. However, in more upland and exposed localities, or in less eutrophic basins, vegetational succession differed not only in timing but also in expression from that described at Hockham Mere.

In this chapter an attempt is made to provide a chronology for the main regional vegetational changes used as a basis of comparison for Flandrian developments. The data from southern Perthshire are alone insufficient to provide a suitable basis for climatic and edaphic inferences, and these are discussed in the context of central Scotland as a whole, including information from other sources. In addition to data discussed in this chapter, further reference to Flandrian forest history in Scotland is given in chapter 1 (section 6).

2. THE IMMIGRATION OF BIRCH AND HAZEL

Available radiocarbon dates indicate the establishment of birch forest in the Teith Valley at some time prior to 9,400 B.P. and in the Amulree district at some time prior to 9,100 B.P. (chapter 11). Birch pollen dominate the pollen spectra in each of the Flandrian pollen diagrams presented here, indicating rapid and widespread immigration of birch. This agrees with Donner's (1958, 1962) evidence from Perthshire that the replacement of open heath vegetation with forest was a relatively rapid process. The importance of birch immigration at this time is reflected in the relatively high birch pollen percentages recorded by Donner for the upland sites of Loch Creagh (altitude 425 m) and Lochan nan Cat (Ben Lawers, altitude _c_. 770 m). Though birch woodland must have been considerably lighter at such altitudes than at lower stations, the evidence from sites in Perthshire as a whole suggests that birch dominated the landscape from lowland valley-bottoms to upland sites that at altitudes in excess of around 300 m were probably restricted to the more favourable south-facing localities.

Evidence from other districts in Scotland indicates the dominance of birch throughout large areas of Scotland in the early postglacial landscape. Pollen diagrams from the central Grampian Highlands (Walker, 1975b) indicate that at this time the main valleys and much of the lower slopes of the Grampians supported a light birch woodland cover. As far north as Wester Ross and Sutherland birch quickly dominated the early Flandrian landscape (Pennington _et al_., 1972), but at some sites in north-west Scotland, and in the Western Isles, heathland continued to dominate until later in the Flandrian (Vasari and Vasari, 1968; Moar, 1969b, 1969c; Birks, 1973). This is also true of south-west Scotland (Moar, 1969a).

Other evidence from Scotland supports the radiocarbon dates presented here. In a section to the south of Perth peat dated to the later part of Godwin's zone IV has been radiocarbon-dated to 9,640 ± 140 B.P. (Callow and Hassall, 1970). The sharp rise in birch pollen has been dated to 9,820 ± 250 B.P. at Loch Kinord, indicating the expansion or immigration of birch in lowland Aberdeenshire at about this time (Vasari, 1977). These dates should be compared with dates available from south-west Scotland indicating the continued dominance of heath vegetation until after about 8,700 B.P. (Moar, 1969a), and those from the Isle of Skye where hazel shrubs replace juniper heath, and birch forest does not expand until some time after 8,650 B.P. (Vasari, 1977). In north-west Scotland the local rise of the birch pollen curve has been dated to about 9,000 B.P. (Pennington _et al_., 1972).

Thus available radiocarbon dates suggest that in eastern and south-eastern districts of Scotland birch dominated the landscape probably by as early as 9,500 B.P. Though the immigration and expansion of birch may have been slightly delayed in upland areas, available evidence suggests that birch spread rapidly throughout the Grampian Highlands and achieved relatively high altitude stands, especially along the southern edge of the mountains. On the other hand the immigration of birch woodland was delayed in western districts of Scotland.

There was also a major contrast between eastern districts and western districts of Scotland in the relative importance of hazel in the regional vegetation. Hazel appears to have been a major canopy species in the main valleys of eastern Scotland, especially in the Midland Valley (Donner, 1957, 1962; Newey, 1968; Vasari and Vasari, 1968; Walker, 1974), but developed a thinner and less widespread cover in areas to the north of the Highland watershed (Pennington et al., 1972; O'Sullivan, 1974; Walker, 1974, 1975b) and in western districts of Scotland (Donner, 1957; Vasari and Vasari, 1968; Moar, 1969a; Birks, 1973).

Although this broad generalisation can be recognised in a general comparison of available pollen diagrams for Scotland, detailed differences between individual diagrams suggest that there were also marked local differences in the relative importance of hazel. Moar (1969a, 1969b) attributed the local development of more dense hazel shrub in western Scotland to the occurrence of calcareous tills, and in the southern Grampians Donner (1962) suggested the greater development of hazel in areas of calcareous rock of the Dalradian series. Conversely, poor stands of hazel in local Flandrian successions are reflected in pollen diagrams from Ireland from areas of lime-deficient soils, and in Scotland from areas where bogs, established in the early Flandrian, were an important landscape feature (Jessen, 1949; O'Sullivan, 1974).

It is likely, therefore, that the local density of hazel in Scotland was governed largely by the relative acidity of soils. Closed hazel woodland would have been restricted to areas with better soils, and birch would have dominated in areas of poorer soils. Pennington et al., (1972) attribute the inability of hazel and mixed-oak forest to spread into northern Scotland during the Flandrian to early Flandrian leaching and soil impoverishment as a result of the prolonged heathland stage (in places dominated by Empetrum heath) that may have dominated the landscape of northern Scotland and parts of western Scotland for the first 1,000 years of Flandrian time. "It seems certain that irreversible changes in soil and water, consequent on normal leaching of newly stabilized soils, had taken place ... before the arrival of birch trees, which had been delayed by the time involved in dispersal from those regions where they had been present during the late-glacial period" (p.277).

Hazel flourished on the south-facing flanks of the south-east Grampian Mountains (Donner, 1962; Walker, 1974) and was especially important in southern Perthshire (see chapter 11). The radiocarbon dates presented in this thesis suggest that the earliest appearance of hazel in this part of the country occurred between about 9,300 and 9,100 B.P., but the main expansion of hazel probably occurred a little time after this. Several dates are available from the Isle of Skye that suggest the rational limit of hazel (Smith and Pilcher, 1973) to have been between about 9,650 and 9,400 B.P. (Birks, 1973; Vasari, 1977). These indicate the earlier immigration of hazel in part of western Scotland than in southern Perthshire. The picture is complicated, however, for at one site on Skye hazel expansion does not occur until 7,500 ± 120 B.P. (Birks, 1973), and in south-west Scotland the immigration of hazel did not occur until about 7,735 ± 155 B.P. Finally, hazel immigration has been dated to 8,910 ± 130 B.P. at one site in northern Scotland (Pennington et al., 1972).

If these radiocarbon dates are all correct, then clearly the spread and establishment of hazel shrubs and trees followed a complex pattern. Of note, however, are the early dates recorded from the Isle of Skye. One hypothesis currently being advanced is that the early Flandrian expansion of hazel in northern Britain commenced from a centre off the west coast of Scotland (Deacon, 1974; Godwin, 1975). Some support for this theory may be found in the dates from Skye. However, if the theory is correct, then since hazel was unable to flourish in the forestless landscape of the early Flandrian of western Scotland this would suggest that podsolisation developed rapidly to restrict the establishment of hazel seedlings.

It is difficult to define when hazel became firmly established in different districts in Scotland. The above dates relate to the points in the relevant pollen diagrams at which the hazel pollen curve begins to rise to sustained high values. With the exception of a non-sequential date of 9,030 ± 140 B.P. from Loch Clair in north-west Scotland (Pennington et al., 1972), other available Flandrian dates refer to periods when hazel had already achieved an important position in the regional vegetation. Until more dates are forthcoming, the dates from southern Perthshire (chapter 11) are accepted. They are collectively consistent, and do not contradict a number of dates from other parts of the British Isles that delimit the immigration of hazel. In addition to the slightly older dates from Skye and Ireland (Smith and Pilcher, 1973), dates from north-west England (Godwin et al., 1957; Hibbert et al., 1971) and Yorkshire (Walker and Godwin, 1954) indicate immigration of hazel into much of northern Britain by about 9,000 B.P. The main expansion of hazel throughout southern Perthshire is thus tentatively placed at about 9,000 B.P.

3. THE ESTABLISHMENT OF MIXED DECIDUOUS FOREST AND THE ROLE OF PINE

It is now becoming quite clear that in southern and eastern districts of Scotland, and particularly in eastern parts of the Midland Valley, mixed deciduous forest became locally interspersed with birch-hazel forests during the Flandrian, and this resulted in the exclusion of the shade-intolerant hazel from large areas. Although the relative pollen percentages are not as high as those recorded for sites in England, evidence from the Midland Valley suggests that elm and oak were important arboreal components in the middle Flandrian (Donner, 1962; Newey, 1968; Brooks, 1976).

Evidence presented in this thesis (chapter 11) indicates the spread of mixed deciduous forest along the main valleys cutting into the southern edge of the Highlands. Although less important than at sites in south-east Scotland, oak and elm are significantly represented in diagrams from sites in lowland and coastal districts of Aberdeenshire (Durno, 1959; Vasari and Vasari, 1968), and oak was more important than elm in sites in south-west Scotland (Moar, 1969a).

In marked contrast to those areas south and east of the main Highland watersheds, pine forests became dominant in the main Grampian Highlands and the Cairngorms (Pears, 1968, 1970; Birks, H.H., 1970, 1975; O'Sullivan, 1974; Walker, 1974, 1975b). The replacement of birch-hazel forest by pine-birch forest in areas north of the Great Glen Fault is interpreted by Pennington et al., (1972) as indicating the gradual deterioration of soils, with pine becoming more competitive as soil acidity increased. Pine became the climax forest type in almost the whole of the forested parts of Scotland north of the Highland Boundary Fault, which may therefore indicate soil deterioration over a vast area.

Pinus is very poorly represented in most Flandrian pollen diagrams from lowland south-east Scotland (Newey, 1968), but higher percentages in some sites suggest scattered pine woods in the Boreal forests of south-west Scotland (Moar, 1969a) and extremely local development of pine stands along the southern edge of the Highlands (chapter 11). Also Pinus is better represented at some upland sites in the Midland Valley where elevation and edaphic conditions favoured its local dominance, as for instance in the Campsie Fells (Eydt, 1960) and parts of eastern Lanarkshire (Fraser and Godwin, 1955). Relatively high-lying sites in the south-east Grampians appear to have supported important pine woods, but birch continued to be the dominant tree in these sites (Donner, 1962). Thus at the time of climax forest development in Scotland an important transition existed between the mainly deciduous forests of the Midland Valley, and the pine-dominated forests of the Highlands. Marked contrasts should therefore be expected in forest composition recorded at sites lying within the transitional zone, as indicated by the sites reported here and earlier by Donner (1962).

Dates for the rational limit of Quercus and Ulmus appear to be diachronous for the British Isles, ranging between about 9,500 for southern England and 7,600 - 7,800 for sites in Ireland and Scotland. The date of 7,640 ± 170 B.P. for the rational Quercus and Ulmus limits at Bigholm Burn in south-west Scotland (Moar, 1969a) is in agreement with dates from Ireland in indicating that the expansion of mixed deciduous woodland was limited in northern and upland districts by poor dispersal or by climatic conditions (Smith and Pilcher, 1973). It is likely, therefore, that the expansion of Ulmus and Quercus in southern Perthshire occurred towards the end of this range of time, though the more favourable climatic and edaphic conditions of south-east Scotland may have resulted in the immigration of these genera at an earlier time than in south-west Scotland and in the uplands of Ireland.

A relatively large number of dates is available from fossil pine stumps from a number of areas in Scotland, and these dates are reviewed by Birks (1975). There is a large range in the values of the dates, but Birks divides them into two main groups, one series of dates from the northwest Highlands of between c. 4,500 and 4,000 radiocarbon years B.P., and another series from the east and south of Scotland that is much more heterogeneous in age, with some dates older than 7,000 B.P. Birks concludes that although the growth of pine may reflect climatic changes in Scotland, the occurrence of pine stumps cannot be taken as evidence in support of a climatic scheme. The immigration of pine is in part related to leaching, acidification and podsolisation of substrates during the Flandrian, and this appears to have occurred much earlier in some areas than in others.

Clearly it would be invalid to assume that the expansion of pine, recorded by increased pollen percentages at three of the sites in southern Perthshire, is related to a synchronous biostratigraphic boundary. Radiocarbon dates are required from the sites in southern Perthshire in order to determine the nature of the immigration of pine in this region. In each diagram (Glenturret, Amulree, Mollands) the expansion of pine occurred before or at the same time as the alder rise, which indicates that it is a non-synchronous feature in southern Perthshire, and that in places it occurred before about 6,500 B.P. (see next section). As discussed above, it is also difficult to provide limits for the immigration of oak and elm in southern Perthshire, and no precise boundaries for these are given in Table 9 (below).

4. THE ALDER RISE IN SCOTLAND

The abundance of *Alnus* pollen recorded in a large number of sites from the British Isles, and frequently interpreted as indicating Sub-zone VIIa in Godwin's (1956) zonation scheme, is generally assumed to represent a vegetational response to a climatic change towards greater oceanity. In a number of sites the marked rise in alder pollen percentages coincides with litho- or biostratigraphic evidence for higher water tables (see chapter 11). However, Hibbert *et al.*(1971) have shown that the alder rise is diachronous throughout north-west Europe, with a broadly east-west gradient of decreasing age. Smith and Pilcher (1973) have elaborated on the pattern for the British Isles, pointing out that three separate definitions have been used to identify the horizon marking the alder rise - the empirical limit, the rational limit, and (occasionally) the 'Mitchell B.A.T.' (Boreal-Atlantic transition). Whichever set of criteria is used, a marked east-west diachroneity can be demonstrated, with the later dates from sites in the north and west and from uplands. The rational *Alnus* limit has a range of dates for the British Isles from about 7,500 B.P. in England to *c*. 5,200 B.P. for sites in northern Scotland and Ireland.

In Scotland the following dates relate to the rational *Alnus* limit: 5,860 ± 100 B.P. at Abernethy in Strath Spey (O'Sullivan, 1974); 5,475 ± 120 B.P. at Bigholm Burn, Dumfriesshire (Moar, 1969a); 5,220 ± 115 B.P.

at Duartbeg, Sutherland (Moar, 1969c); and 6,490 ± 125 B.P. for West Flanders Moss, Stirlingshire (Sissons and Brooks, 1971). These dates taken alone illustrate that the earlier dates for the alder rise are found in sites to the south and east. Three dates are also available for the empirical limit of the alder rise ("the point at which pollen of the species first becomes consistently present, i.e. for a number of consecutive samples" - Smith and Pilcher, 1973, p.904). These are 6,250 ± 140 B.P. at Loch Sionascaig (Sutherland/Wester Ross border), 6,520 ± 145 B.P. at Loch Clair (Wester Ross - Pennington et al., 1972), and 6,513 ± 65 B.P. at Loch Maree, Wester Ross (Birks, 1972).

Since the empirical limit relates to the first appearance of alder pollen and not to the beginning of the main alder rise, the last three dates listed above probably do not relate to the main regional alder expansion in north-west Scotland. It has been shown (chapter 11) that alder immigrated into some sites in southern Perthshire in advance of the main regional expansion that reflects regional climatic change. This may thus be a common phenomenon for other regions. Thus more emphasis is placed on the dates relating to the rational Alnus limit, since these probably relate to the main regional expansion of alder in the relevant areas.

The site of West Flanders Moss lies close to the sites in southern Perthshire, and this date suggests that the main alder rise occurred earlier in the south-east of Scotland than in other districts. Though alder may have expanded earlier on the carse clays and generally low levels of the Forth Valley than in the Teith Valley and higher sites, it is assumed that the main alder rise in southern Perthshire would not be greatly metachronous in comparison to north Stirlingshire. Thus the main alder rise identified at Mollands (Fig. 24), Cambusbeg (Fig. 19) and Glenturret (Fig. 26) is thought to be roughtly synchronous in southern Perthshire at about 6,500 B.P. This requires verification, however, for there remains the problem that local edaphic conditions might have favoured an earlier expansion of Alnus at some sites in Scotland than at others, and the local development of alder carr may have resulted in the over-representation of Alnus pollen to such an extent that the rational Alnus limit in resultant pollen diagrams is extremely difficult to determine.

5. THE ELM DECLINE IN SCOTLAND

In some pollen diagrams from Scotland a decline in elm pollen is clearly demonstrated. The decline is clearest in diagrams from the south and east of the country (Donner, 1962; Durno, 1965; Newey, 1968; Vasari and Vasari, 1968; Moar, 1969a). This feature can also be recognised in diagrams from the Highlands and north and west Scotland, though in many Scottish pollen diagrams percentages of Ulmus pollen are very low throughout the Flandrian, so that it is often difficult to determine the precise horizon that relates to the Elm Decline (O'Sullivan, 1974; Walker, 1975c). In diagrams from the extreme north and west elm pollen grains virtually disappear in the late Flandrian spectra (Vasari and Vasari, 1968). Pennington et al. (1972) attribute the reduction of elm pollen recorded in sites in north-west Scotland to a decline in the general regional pollen rain of the north-west Highlands of elm pollen derived by long-distance transfer from elm stands farther south. How far north elm was able to migrate is not presently clear, but the genus was certainly poorly represented in sites north of the Highland Boundary Fault.

Hibbert et al. (1971) have shown that the Elm Decline is broadly synchronous throughout north-west Europe, at about 5,000 B.P. Smith and Pilcher (1973) have compared 29 radiocarbon dates for the Elm Decline from the British Isles, and with the exception of 2 they range from about 5,300 to 4,800 B.P. One of the exceptions is a date from Flanders Moss, Perthshire of 4,750 ± 120 B.P. (Turner, 1965). There are, however, no other dates from Scotland that relate precisely to a clear boundary indicating the Elm Decline. Dates available from sites in north-west

Scotland are not helpful because of the poor representation of elm pollen (Pennington et al., 1972), though interpolation between dates from Loch Sionascaig indicates a date for this event at about 4,750 B.P. In view of the overwhelming evidence in favour of a broadly synchronous horizon for the British Isles the Elm Decline is interpreted here as c. 5,000 radiocarbon years old.

In a number of diagrams from Scotland the Elm Decline coincides with a marked overall reduction in arboreal pollen percentages and with the appearance of pollen of species suggesting agricultural activity. This is quite clearly illustrated in a diagram published by Donner (1962, Fig. 9) relating to sites in Perthshire. Of the sites analysed by the author the Elm Decline is most clearly represented in the Mollands diagram (Fig. 24). The clear relationships outlined by Donner are not repeated at Mollands, for arboreal pollen continue to be important following the Elm Decline, though a slight decrease in percentages occurs.

More detailed evidence is required in order to determine the nature of the Elm Decline in different parts of Scotland, and its precise relationship to lithostratigraphic and biostratigraphic changes. More dates are required to test the hypothesis that the Elm Decline is directly related to anthropogenic factors. It would appear that in this respect efforts should be concentrated in southern and eastern parts of Scotland, where the Elm Decline is more clearly expressed in pollen diagrams, and where there is accumulating evidence for the activities of Man. That Man's activities affected the vegetation of central Scotland shortly after the Elm Decline is indicated by a date of 4,120 ± 105 B.P. from a horizon near Stirling (Sissons and Brooks, 1971) from which wooden trackways and trees with axe marks had previously been noted (Sinclair, 1796).

6. AN ABSOLUTE CHRONOLOGY FOR FLANDRIAN VEGETATIONAL HISTORY IN SOUTHERN PERTHSHIRE

In view of above discussions a tentative chronology can be assigned to the Flandrian pollen diagrams available for central and southern Perthshire. Table 9 is a generalised scheme for vegetational development at lowland and upland sites in Perthshire, in which the three pollen diagrams published by Donner (1962) have been considered in addition to the diagrams analysed by the author. Two of Donner's sites, Loch Creagh (NN 904 443) and Lochan nat Cat (Ben Lawers - NN 649 425) are farther north than any of the sites in southern Perthshire. Loch Creagh is at approximately the same altitude as Glenturret (425 m), whilst Lochan nan Cat is much higher (770 m). Donner's third site, Loch Mahaick, lies close to but to the east of Callander at an altitude of 230 m (NN 705 072).

TABLE 9 Generalised scheme for the forest history of central and southern Perthshire, comparing upland and lowland sites

Approximate absolute date (B.P.)	Lowland sites (4 sites below 250 m)	Upland sites (3 sites over 400 m)
	alder-birch-hazel	birch-alder-pine
5,000		
	alder-oak-elm	birch-alder-hazel-(oak)
		birch-(pine)-alder
6,500		
	birch-(pine)-oak-elm	birch-elm-oak-hazel-(*Salix*)
	birch-hazel	birch-hazel
9,000		
	birch	birch-juniper
9,500		
	juniper-birch	juniper-birch
10,000		
	(Loch Lomond Stadial/Flandrian transition - juniper and *Empetrum* heaths)	

The boundaries in Table 9 are probably not exactly synchronous throughout Perthshire, but it is unlikely that any great variation occurs. In the table only the dominant forest components are given, and these are listed for any single horizon in apparent order of importance. Where a genus is given in brackets, this indicates that that genus was only locally important, being variably represented in either upland or lowland pollen diagrams.

In comparing the diagrams it is difficult to rank them in terms of the relative importance of arboreal pollen. In any case this may be highly misleading, as variation in the relative importance of local over-representation of non-arboreal pollen can seriously affect the arboreal/non-arboreal pollen ratios. Thus much higher arboreal pollen percentages are recorded for the mixed deciduous forest period at Lochan nat Cat and Loch Creagh than at the lower and more southerly sites. It is likely that not only forest composition but also forest density varied throughout southern Perthshire at all times during the Flandrian. Whether closed forest existed at the altitude of Lochan nan Cat, as claimed by Donner (1962), is not certain. If Faegri and Iversen's (1964) thesis that 10% and less of non-arboreal pollen indicate closed forest conditions is correct, then according to Donner's data this would indicate forest growth in Perthshire at higher altitudes than present-day limits (Poore and McVean, 1957). Since both elm and oak achieve pollen percentages in excess of 10% in Godwin zones VI and VIIa at Lochan nat Cat, this would suggest that mixed deciduous woodland locally achieved relatively high altitudes.

The main contrasts between the upland and lowland sites in general are the greater importance of birch at upland sites throughout the Flandrian, the greater importance of pine and shrubs at higher sites, and the greater importance of alder at lower sites, though this tree was widespread throughout Perthshire after 6,500 B.P. Within the eight sites used in constructing Table 9 there is variation in the representation of oak and pine, but this does not appear to follow any simple pattern. It is likely that this reflects sudden and important changes in forest composition in an area which was transitional between dominant forest types (see above). Godwin has produced a diagram indicating dominant forest types for the British Isles at c. 5,500 B.P. (1975, Fig. 164). The generalised scheme (Table 9) for the lowland sites is in agreement with his concept of a dominant alder-oak-elm forest for southern and central Scotland, and that for the upland sites is transitional between the mixed deciduous forest and the pine-birch-alder forest suggested for the Highlands.

In order to be more confident about a scheme such as that outlined in Table 9, radiocarbon dates from some of the sites in Perthshire are essential. In addition, absolute pollen counts would better reflect the importance of arboreal components at each site for more meaningful comparisons. However, if the broad outline of the scheme can be accepted, and if the use of the chronostratigraphic boundaries discussed in earlier sections is valid, then this provides an approximate time-perspective for discussions of the climatic and edaphic conditions reflected in the vegetational successions.

7. CLIMATIC AND EDAPHIC CONDITIONS DURING THE FLANDRIAN

Faunal and floral records from Europe as a whole indicate that following the rapid climatic improvement at the beginning of the Flandrian, a mid-Flandrian thermal maximum ('climatic optimum') occurred with mean summer temperatures about 2^{o}C higher than the present in western Europe (Godwin, 1975). The thermal maximum is generally held to equate with the end of the Boreal period and the Atlantic Period, which in turn suggests that optimal thermal conditions were achieved between about 7,000 and 5,000 B.P. However, there is no clear boundary for the beginning of the 'climatic optimum', and in view of the incorrect assumptions based on floral assemblages from the Lateglacial (see chapters 9 and 10) caution is necessary in making climatic inferences from the Flandrian forest immigration sequence. It may be that temperature achieved a maximum early in the Flandrian, which was maintained until about 5,000 B.P. or even later. Coleopteran studies are likely to provide more precise parameters than floral records.

There is also a difficulty in defining the close of the so-called climatic optimum. The time assumed to indicate the beginning of climatic deterioration is also the date generally held to indicate the beginning of widespread human interference on vegetational patterns, and it is difficult to decide the relative importance of the separate factors in any one region. In addition to climatic changes and human interference, vegetational changes can also result from changing edaphic conditions that need not be directly related to climatic factors. Thus the immigration of pine is related to increasing leaching of soils with time (Birks, 1975), and the expansion of the relatively thermophilous <u>Carpinus</u> in England after 5,000 B.P. can have a variety of explanations, including human interference, climatic thresholds, and edaphic changes (Godwin, 1975). Because of the complexity of factors controlling Flandrian vegetation developments, it may be some time before a major thermal transition can be confidently demonstrated.

There is little in the evidence from southern Perthshire to indicate significant thermal variation during those parts of the Flandrian investigated. Temperatures remained favourable during much of the Flandrian to allow the immigration of warmth-loving genera such as hazel, oak, elm and alder, culminating in dominant mixed deciduous woodland in the valleys of the south-east Grampians some time before 6,500 B.P. (Table 9). The Elm Decline is interpreted as a result largely of anthropogenic control in Perthshire. Following this event, birch and hazel regeneration took place. The re-expansion of hazel is interesting, for this plant requires favourable summer temperatures and is susceptible to spring frosts (Birks, 1972). Thus the increased representation of this plant following the Elm Decline, especially in view of evidence showing that hazel was often used in trackways as early as 4,500 B.P. and was coppiced by prehistoric man (Clapham and Godwin, 1948), suggests that thermal deterioration could not have been marked. Hazel regenerated at other sites in Perthshire, even in the high-lying site of Lochan nan Cat (Donner, 1962). In addition, Quercus continues to be an important arboreal element in the pollen diagrams following the Elm Decline (Mollands, Loch Mahaick, Loch Creagh and Lochan nan Cat). The successful continued flowering of this temperate forest component, as well as of hazel, suggests that if climatic conditions changed at the time of the Elm Decline then this change could not, initially at least, have been a major thermal decline.

There is no doubt, however, that the forest belts of north-west Europe extended farther north and higher into the mountains in the period between 7,000 and 5,000 B.P. than they do today (Godwin, 1975). In a comprehensive study of macrofossil evidence from the Cairngorms, Pears (1968, 1970) has shown that the Caledonian forests extended as high as 2,600 ft. (790 m) in places, and were commonly well developed at 2,300 ft. (700 m). This can be compared with the present actual tree limit of 1600 ft. (490 m) (Pears, 1967) and the natural (potential) tree-line of 2,000 ft. (610 m) to 2,250 ft. (685 m). Donner's evidence from Lochan nan Cat (1962) would suggest a tree-line at least to about 2,350 ft. (715 m) in parts of the south-east Grampians during part of the Flandrian. Thus mean summer temperatures have been higher in the middle Flandrian than they are today, but there is no clear evidence as to the precise stratigraphic horizon that marks the thermal decline.

It may be that the thermal decline took place very gradually following, and as a result of, the increased oceanity that characterised the Atlantic period. The Boreal-Atlantic transition has been defined as that horizon at which a marked expansion of alder occurs, though this event has been shown to be diachronous in north-west Europe. The major expansion of alder is thought to have resulted from increased oceanity in the British Isles following the rising Flandrian sea-levels created by the melting of the continental ice sheets (Godwin, 1975). The culmination of the Flandrian sea-level transgression has recently been dated to 6,490 ± 125 B.P. (Sissons and Brooks, 1971) for the Forth Valley, which coincides with the dates of the alder rise from parts of Scotland and Ireland (Smith and Pilcher, 1973). In eastern Fife the transgression maximum has been dated to between 7,605 ± 130 and 5,830 ± 110 B.P. (Chisholm, 1971).

On available evidence it is difficult to separate the inter-related factors of oceanity and temperature in attempting to decipher past climatic changes. The evidence from southern Perthshire is consistent with the view that favourable temperatures were maintained throughout those parts of the Flandrian that have been recorded, but that a change from relatively dry to more oceanic conditions resulted in marked vegetational changes at about 6,500 B.P. The Elm Decline appears to have resulted more from anthropogenic affects than from climatic changes. A problem exists, however, in explaining the dominance of elm over oak in some upland sites (see chapter 11, section 4). It is not clear what prevented oak becoming dominant over elm, as occurred in the lowland and more southerly sites. In chapter 11 it was suggested that a change in climatic conditions may have been responsible, for elm is the more demanding species, but other evidence (this chapter) militates against this.

By analogy with modern day soil-vegetation associations a simplified model of Flandrian soil development in Perthshire is implied in Table 9 and by other evidence presented in this thesis. By world standards, the present-day soils of Scotland as a whole are relatively young, and are largely classified as podsols, semi-podsols and rankers (FitzPatrick, 1964; Ragg, 1973). However, the development of mixed deciduous forest throughout large areas of Perthshire implies that brown forest soils were dominant, especially in lowland areas and on gently-sloping terrain.

Following the close of the Loch Lomond Stadial, soil-forming processes may have been initially slow on the raw substrates and immature soils characteristic of that period (chapter 9). However, the rapid development of birch woodland followed by a birch-hazel association within the first 1,000 years of Flandrian time suggests that brown earths had started to form early in the Flandrian. Initially the brown earth soils may have been characterised by a moder rather than a mull humus. The gradual development of a dominant alder-oak-elm forest implies that brown forest soils continued to mature, at least until about 5,000 B.P., on lowland sites. During the Boreal (or middle Flandrian) it is likely that a relatively deep mull humus layer had developed, with a pH ranging between 5.5 and 6.5, the soil being well aerated and supporting large populations of soil micro-organisms.

Brown forest soils appear to have also characterised large parts of the upland areas of Perthshire, in view of the evidence from Amulree, Glenturret, and that provided by Donner's studies (1962). It is probable that a mosaic of soil types existed, with rankers associated with drift-free hill summits and steep slopes, podsols in areas where heathland was maintained, and gleyed soils in waterlogged sites. However, taking the evidence from the eight available pollen diagrams collectively, mixed deciduous forest was dominant throughout Perthshire implying that brown earths, varying in profile maturity, profile depth and thickness of mull layer, predominated.

The most favourable soil conditions probably existed during the late Boreal period, when conditions were relatively dry, and mixed birch-oak-elm forest characterised most of the Perthshire slopes. The increased oceanic conditions after 6,500 B.P. would have resulted in an expansion of areas liable to waterlogging, and soils would have been generally wetter, thus favouring the establishment of alder seedlings. In addition, blanket-peak-forming communities began to replace deciduous forest on the flatter mountain summits throughout the British Isles (Pennington, 1969). Thus, after 6,500 B.P., the importance of brown forest soils declined in Perthshire, though the continued records of mixed forest at both upland and lowland sites suggests that they continued to be an important soil type in this area.

The increased representation of pine at upland sites after 5,000 B.P. suggests that soils were becoming more and more acid (culminating in the iron-humus podsol which is present today). The phase of dominant heathland recorded in all of Donner's (1962) pollen diagrams in the late Flandrian shows that podsolisation of brown forest soils continued in the area, and this was greatly accelerated by deforestation as a result of man's activities. There are no dates available from this region for the main deforestation phase, but evidence from farther north suggests that deforestation was accelerated between about 3,600 and 1,500 B.P., and that the bulk of forest clearance occurred during the Dark Ages (1,500 to 1,000 B.P.) (O'Sullivan, 1973). As in many other parts of the British Isles, the landscape of Perthshire has remained largely forestless until the Forestry Commission started modern planting in 1919.

The main problem in reconstructing the history of soil development in the British Isles is to determine to what extent podsols had developed in those areas originally dominated by mixed deciduous forests prior to the main clearance phases of the late Flandrian. In his detailed study of soil genesis in south and east England, Dimbleby (1962) has shown that few soils in these areas have been podsols since the Atlantic, but that the majority are secondary, having arisen as a result of large-scale forest clearances by man. Thus it is possible that brown forest soils continued to be an important element of the landscape in Perthshire until well after 5,000 B.P. Podsols can develop very rapidly following widespread forest clearance (Dimbleby, <u>op. cit</u>.).

Almost all of the present forest stands in Perthshire are plantations, introduced mainly by the Forestry Commission. Only a few scattered occurrences of mixed deciduous woodland exist, such as that on the banks of the Keltney Burn, about 10 km north of the most easterly shore of Loch Tay, and locally on steep slopes at Glen Fonvuick near Killiecrankie. These include <u>Quercus</u> spp., <u>Betula</u> spp. and <u>Ulmus glabra</u>, along with <u>Corylus avellana</u> and <u>Sorbus aucuparia</u>. Little in detail has been published concerning these associations, but the presence of Fraxinus excelsior and Hedera helix indicates that they are not relics of natural woodland. They are usually associated with rich field communities and are confined to calcareous rocks (such as the Dalradian Limestone outcrops at Keltney Burn and Glen Fonvuick), giving rise to fertile brown forest soils with a rich mull-humus (McVean and Ratcliffe, 1962). Though not entirely natural communities, stands such as these give some idea of the likely soil profiles that developed beneath mixed deciduous forests during the middle Flandrian, though the soils would have been thinner on the generally less calcareous rocks of most of Perthshire. (Analysis of surface pollen spectra from such communities would also provide comparisons for fossil spectra, which may lead to more objective interpretations of Flandrian pollen zones.)

It is interesting to compare the soil history of central and eastern Scotland with that of the Highlands and the north-west. It appears that heathland communities dominated large areas of the Highlands and northern Scotland for the first 1,000 years or so of Flandrian time (Moar, 1969a, b, and c; Pennington et al., 1972; O'Sullivan, 1974). Pennington et al. suggest that this resulted in prolonged leaching from which the soils of northern Scotland never recovered. An acid mor-humus developed, and birch and hazel were unable to colonise large areas because of the acid surface layers. Similarly O'Sullivan (1974) suggests a similar development for parts of the Cairngorms, for "... the delay of the arrival of tree species in the area may have been crucial for its subsequent ecological development. Under areas of Empetrum and Calluna-dominated vegetation, podsolisation may have begun at even this (Early Flandrian) early stage" (p.53).

Thus a fundamental contrast can be made between central and eastern districts of Scotland on the one hand, and northern and western regions on the other. A crucial factor was the time taken for trees to colonise a region, for where forest became established early, brown forest soils developed, and nutrient recycling was an important process in maintaining a mull-humus layer. However, once an acid mor-humus layer had developed, in the absence of early forest development, then only those species that could colonise acid surfaces would have immigrated. Pine became dominant in these districts, and the litter derived from pines would have maintained an acid mor-humus. Although climatic conditions may have been sufficiently mild throughout Scotland to potentially permit the growth of mixed deciduous forest during the Boreal, the soils of Scotland may have been determined in the early Flandrian by the time required for trees to migrate from Lateglacial refugia, which would have in turn determined subsequent vegetational developments. Another possibility is that podsolisation was so rapid in the early Flandrian, especially on the acid gneisses and sandstones of the north-west, that immigration of forest genera was inhibited almost from the beginning of the period. This could better explain the apparent conflict between the early appearance of hazel in the west of Scotland and its inability to expand in the region (see section 2).

The vegetational sequences reflected in the pollen diagrams from Perthshire, and the analysis of deteriorated pollen at some of these sites (chapter 6) reveals that in those areas where mixed deciduous woodland developed there was an uninterrupted succession until about 'late Boreal' times. The curves for deteriorated pollen indicate that there was little inwash of material from surrounding slopes (Fig. 33) in the early parts of the Flandrian, and in fact the lowest percentages of deteriorated pollen are recorded from early Flandrian levels in all of the diagrams. Following the establishment of mixed deciduous woodland in southern Perthshire lower water tables are recorded by mire stratigraphy at some of the sites (chapter 11) and a dramatic increase in the percentages of deteriorated pollen occurs at all of the sites (chapter 6). In each case this marked increase in the number of deteriorated pollen grains occurs before the main alder rise, and appears to coincide more with the reduction of <u>Corylus</u> pollen percentages following the main birch-hazel phase.

In most cases the increased percentages of deteriorated pollen are interpreted as reflecting inwashed grains, derived either from basin-edge deposits or from soils in surrounding catchments. The evidence points to the late Boreal period as being important in southern Perthshire in that water tables were significantly lowered, and dried soil surfaces, particularly on steep slopes and stream banks, may have been subjected to erosion. However, as discussed in chapter 6, the analysis of deteriorated pollen percentages is not straightforward, and many more results are required to confirm the relationships suggested by the data from southern Perthshire. It is difficult to establish whether or not deterioration of pollen grains has taken place in situ in a particular sediment or prior to pollen deposition. There are also individual features in the frequency curves for deteriorated pollen that as yet have no adequate explanation, such as why deteriorated pollen totals at Mollands (Fig. 24) should decline sharply at the Elm Decline, when it might be expected that forest clearance would lead to increased inwash into the basin. Clearly there is a need to study carefully the sequence of deposits from the late Boreal onwards, but this has been sadly restricted in the present study.

8. CONCLUSIONS

In comparing the pollen diagrams from southern Perthshire with other published pollen diagrams and relevant radiocarbon dates from the British Isles it has been possible to suggest a chronology for Flandrian events applicable to this part of the country. However, only one widely recognised Flandrian biostratigraphical boundary is regarded as synchronous for the British Isles, and that is the Elm Decline. This is the only boundary referred to in the scheme outlined in Table 9 that relates to the reduction or disappearance of a species. The others are defined on the basis of the arrival of forest genera. In the words of Smith and Pilcher (1973, p.911) "Factors such as migration rate, soil development and inertia of the existing vegetation ... clearly do not affect the decline of a species in the way they affect the rate of its establishment".

Since most of the boundaries referred to in Table 9 are metachronous, some more obviously than others, it would be much preferable to obtain radiocarbon dates from relevant boundaries from sites in southern Perthshire to advance knowledge of metachronous vegetation succession in the British Isles rather than to adopt the converse approach used in this chapter. The eastern central district of Scotland lacks a detailed radiocarbon-dated Flandrian profile, and this is clearly a priority for future research. Meanwhile Table 9 is advanced as a working-model until more precise information is forthcoming.

In southern Perthshire birch woodland began to replace juniper and Empetrum heaths early in the Flandrian, and by 9,500 B.P. birch woodland was dominant in the area. At about 9,000 B.P. hazel expanded rapidly in the region, becoming co-dominant with birch, and probably also forming pure hazel woods on the better soils of the lowlands. Birch-hazel associations developed on both upland and lowland soils, and these were probably brown forest soils that initially may have developed a moder rather than a mull-humus. In the lowlands the climax forest was of oak, elm and birch, which gave way to an alder-oak-elm forest at about 6,500 B.P. On upland sites the mixed deciduous forest was lighter, with hazel and Salix associated with less dense stands. This gave way to a birch-alder-hazel (in places associated with oak) or a birch-alder-pine forest. Brown forest soils with mull-humus probably characterised much of Perthshire under the Boreal forests. Forest clearance resulted in heathland replacing forests and podsols replacing brown forest soils throughout Perthshire. Though forest clearance appears to have begun at the Elm Decline (5,000 B.P.), it is difficult to establish when podsolisation processes may have begun.

CONCLUSIONS

One of the prime objectives of this work has been to test the validity of the Loch Lomond Readvance glacial limits established for western Perthshire by Thompson (1972). On the basis of palynological investigations and associated radiocarbon dates the limits proposed by Thompson for southern Perthshire appear to be valid, and this in turn therefore supports the concept that Loch Lomond Readvance limits can be reconstructed for Scotland by the mapping of fresh hummocky drift (Sissons, 1974a, 1976a).

At two of the three Lateglacial sites investigated in southern Perthshire biostratigraphic evidence for Lateglacial deposits has been found where the widely-recognised, tripartite lithostratigraphic sequence of minerogenic-organic-minerogenic Lateglacial sediments is absent. A number of basal cores were inspected at both sites, and at one site the basin was bored systematically in order to locate the deepest point. The evidence is interpreted as indicating that at some sites in the Highlands and the Highland Border, conditions of soil instability persisted throughout the Lateglacial Interstadial. Since organic Interstadial deposits have failed to accumulate at some sites it is invalid to use lithostratigraphic data alone in relative dating; biostratigraphic analysis is essential, and in the palynological investigation of Lateglacial sediments from sites described in this thesis the type of boring equipment employed has been found to be a crucial factor. Because of problems of disturbance and contamination resulting from the use of Hiller borers, much more emphasis has been placed on palynological data based on samples obtained by piston corers.

Evidence from Lateglacial deposits in southern Perthshire suggests that plant colonisation commenced shortly after 13,000 B.P., indicating deglaciation of the Teith Valley by that time. Plant successions followed an uninterrupted sequence between about 13,000 and 11,000 B.P., and no support can be found for an equivalent to the Bölling-Older Dryas-Alleröd sequence of continental stratigraphy. The term Lateglacial Interstadial is used to refer to that period between c. 13,000 and 11,000 B.P., and the Loch Lomond Stadial to the period between about 11,000 and 10,000 B.P. during which the Loch Lomond Readvance ice was at its maximum extent. The Loch Lomond Stadial is recognised by a clear vegetational revertence phase in the Lateglacial pollen diagrams.

Pollen spectra from early Lateglacial deposits reflect an initial period of colonisation by open-habitat taxa, and throughout the Lateglacial Interstadial there gradually developed a closed grassland, with juniper, dwarf birch, willow, and occasional copses of tree birch invading the major valleys of the southern Grampians. Moss heaths and poor grassland communities were more characteristic on upper slopes, and in exposed localities the vegetation cover remained incomplete which resulted in continued soil instability at some sites throughout the Lateglacial. By about 11,000 B.P. climatic conditions were much harsher, and this is reflected in the biostratigraphical and lithostratigraphical evidence for the break-up of existing plant communities and for widespread cryoturbation and solifluction. A tundra landscape developed throughout southern Perthshire during the Loch Lomond Stadial. Rapid climatic amelioration shortly before 10,000 B.P. resulted in the cessation of solifluction processes, and a plant succession was initiated that led to the immigration of birch woodland into parts of this area by about 9,500 B.P.

The radiocarbon dates from sites in southern Perthshire have been compared with other available dates from Scotland, and it is evident that chronostratigraphic boundaries are at present poorly defined, and may bear little relationship to times of major climatic change in Scotland. Though the boundaries 13,000 B.P., 11,000 B.P. and 10,000 B.P. have been employed in the chronostratigraphic scheme outlined in detail in chapter 10, many more dates are required to test the validity of giving chronostratigraphic definitions to major environmental changes. It would appear that the boundary of 10,000 B.P. is significantly younger than the date of the climatic improvement that marked the close of the Loch Lomond Stadial.

In using basal basin sediments to date morphological or stratigraphic features, two considerations would seem to be of paramount importance at present. Firstly, for a variety of reasons (Chapters 8-10), the basal sediments, and hence radiocarbon dates of them, can only provide a minimal date for underlying deposits. Secondly, many of the radiocarbon dates published from Lateglacial and early Flandrian deposits so far from Britain are based on gyttja samples. This applies also to the majority of the dates from southern Perthshire. There is a growing awareness of the possibility of hard water error being characteristic of gyttja material (R.E.G. Williams, personal communication), and recently a piece of wood has been found encased in gyttja that gives a date almost 2,000 years younger than the sediment (G.R. Coope, personal communication). Though there are dates based on macrofossil material that suggest that the errors in dates based on gyttja may not always be large, until future research provides clearer details as to the nature of this problem the dates based on gyttja described in this thesis should be viewed with suspicion.

When analysing profiles from within the Loch Lomond Readvance limits, as at Mollands and Glenturret, a problem exists in that a conclusion based on the absence of Lateglacial sediments is essentially a negative argument. There may be an explanation for the absence of deposits of a certain age which is not related to the age of formation of the basin containing the deposits. Thus, for example, sedimentation began at Glenturret only as a consequence of the development of a perched water table (chapter 5), and the commencement of sedimentation would appear to have been delayed for a period significantly greater than 1,000 years after the melting of Loch Lomond Readvance ice. It would obviously be an advantage to concentrate on sites with bases that are below present water tables, but sites within the Readvance limits have been found to be exceedingly rare. Thus the only alternative in attempting to test the validity of the age of deposits attributed to the Loch Lomond Readvance is to test as many available sites as possible within a specific area.

However, the evidence from the Teith Valley indicates that the Mollands basin was formed during the melting of the Loch Lomond Readvance ice near Callander. A clear terminal moraine has been mapped in this vicinity, and two Lateglacial profiles have been established immediately downvalley from the moraine. The Mollands basin is a kettle hole that lies immediately within the terminal moraine. Radiocarbon dates from Tynaspirit indicate sedimentation from about 12,750 B.P. onwards in this Lateglacial site, but the earliest date available from the base of the Mollands deposits is 10,670 ± 85 B.P. Further, the gradual transition from minerogenic to organic sediments at the base of the Mollands deposits has been interpreted as indicating minerogenic sedimentation that is independent of local soil changes around the basin, and thus it seems probable that the minerogenic layers reflect ice or snow melt around Mollands during the Loch Lomond Stadial/Flandrian transition. A distinction can be made between the basal deposits at Mollands and Lateglacial/Flandrian transition sediments from other sites. Normally this transition is marked by a sharp lithostratigraphic horizon, which probably indicates that the nature of the sediments is essentially interdependent with local vegetational and soil changes, which were probably relatively rapid at this time.

In this thesis use has been made of the analysis of deteriorated pollen. The causes of different classes of deterioration (<u>viz</u>. corroded, amorphous, broken and crumpled pollen grains) are difficult to explain. However, in general terms it has been found that the overall totals of deteriorated pollen grains follow similar patterns in different Lateglacial sites. Thus totals are highest in the early Lateglacial Interstadial and Loch Lomond Stadial deposits, and they decline in the later part of the Interstadial and most abruptly in the early Flandrian. The deterioration is usually breakage and crumpling of grains, implying physical destruction as a result of transportation during times of increased erosion. However, the increased representation of corroded grains in Loch Lomond Stadial clays has been interpreted as indicating the washing-in of soils that had gradually developed during the Lateglacial Interstadial.

In analysing Flandrian deposits from southern Perthshire several biostratigraphic boundaries have been found to be common to each profile, indicating a basically similar vegetational history at each site. These are the expansion of juniper, the immigration and expansion of birch woodland, the development of a dominant birch-hazel woodland, and the decline of hazel following the immigration of elm and oak. At three sites the main Alnus rise is recognised, and the Elm Decline is positively identified at only one site. These horizons are assumed to be more or less synchronous for the region, and a chronological outline for the immigration sequence is based on comparisons of radiocarbon dates published for the British Isles as a whole.

The climax forest of lowland Perthshire was a mixed oak-elm-birch association which was probably associated with brown forest soils. On upland sites mixed deciduous woodland was lighter and birch was the most important tree. Hazel and Salix were also associated with the less dense forest stands. The climax forest on upland sites varied between birch-alder-hazel and birch-alder-pine, and oak also invaded some of the higher valleys. At about 6,500 B.P. the climate changed from being relatively dry to one with markedly oceanic characteristics. Evidence for this is found in mire stratigraphy and in changes in types and amount of deteriorated pollen at some sites. However, the evidence from southern Perthshire does not appear to fit the concept of a 'climatic optimum' that ends at about 5,000 B.P.

All the evidence points to the late Boreal-Atlantic transition as being an important one in terms of environmental change. Water tables were markedly lowered at this time, mires were altered significantly at some sites, basin-edge deposits and soils were eroded, and fen communities became important locally. These fen communities became so dominant in some areas that they continued to flourish after the transition to oceanic conditions and higher water tables at the Boreal-Atlantic transition. The Boreal-Atlantic transition was clearly an important environmental threshold, but with the sometimes contradictory and confusing evidence from deposits of this age (chapters 6 and 12) more detailed investigations are necessary.

In developing a Flandrian type-profile for the south-eastern Grampians and areas of the Midland Valley that are close to the Highland Boundary Fault, account must be taken of the highly variable forest composition that characterised the mid-Flandrian in particular. Whilst analyses from the lowland sites supported Godwin's (1975) concept of a dominant alder-oak-elm forest in the Midland Valley at about 5,500 B.P., the upland sites, as with the higher sites from Perthshire investigated by Donner (1962), are transitional between that type of forest and the pine-birch-alder forest that characterised the Highlands at that time. It is intended by the author to use Mollands as a type-profile for the Flandrian, with absolute pollen counts and radiocarbon dates related to specific horizons. However, this can only be regarded as typical for lowland valleys and the eastern Midland Valley, and care must be taken in reconstructing the vegetational history of upland valleys and the higher slopes of the southern edge of the Grampians. Available evidence points to the likelihood of major changes over relatively short distances in such situations.

The analysis of deteriorated pollen grains has revealed marked increases in the proportions of deteriorated grains in late Boreal deposits, and this has been interpreted as largely indicating collapse of basin-edge deposits. If this has indeed occurred then older sediments will have been incorporated into mid-Flandrian and late Flandrian deposits. This may be a common problem in mid- and late-Flandrian basin deposits. It is a major conclusion of this thesis that the analysis of deteriorated pollen grains should be included in palynological investigations of basin deposits, especially where a radiocarbon-dated type-site is to be developed. It is suggested that several preliminary pollen diagrams, including data on deteriorated grains, should be produced for several sites, and thus more time-consuming efforts (absolute pollen counts, cross-checks on cores for radiocarbon samples, etc.) can be concentrated on those sites for which re-sedimentation and other problems are minimised or at least clearly defined.

Inevitably these investigations have resulted in many more unanswered questions than the ones that prompted a start to the project. The number of potential lines of enquiry appear to the author to be inexhaustible, though there are several more prominent lines that appear to promise valuable rewards. It is hoped that this research will be continued and expanded to cover these lines of enquiry. It is especially important to obtain absolute pollen counts from Lateglacial sediments in order to avoid the difficulties of basing palaeobotanical conclusions on relative pollen percentages. Difficulty has been experienced in this work in deciding whether or not some fluctuations in pollen curves were meaningful, especially at important times of transition. In a number of cases, especially in the Loch Lomond Stadial/Flandrian transition sediments (e.g. at Mollands), it is clear that some fluctuations were caused by changes in the influx of other taxa. In addition, the problems of basing climatic inferences on palaeobotanical data are now fully realised. To better understand the Lateglacial palaeoenvironmental environments of southern Perthshire it would seem imperative to use absolute pollen counting in at least one site in the future, and to obtain faunal evidence for palaeoenvironmental changes in addition to palaeobotanical evidence.

APPENDIX 1

Sites in Scotland with pre-Loch Lomond Stadial deposits (see Fig. 35)

1. Whitrig Bog (Mitchell, 1948; Conolly, 1961)
   E of Moffat Hills, S of Lammermuir Hills, 3 mls. N of Tweed.

2. Garscadden Mains (Donner, 1957)
   SW of Bearsden, Glasgow. NS 533713

3. Loch Mahaick (Donner, 1957, 1958)
   7 mls. E of Callander. NN 705072

4. Drymen (Donner, 1957; Vasari and Vasari, 1968)
   Muir Park Reservoir, 4 mls. N of Drymen. NS 490923

5. Oban 1 (Donner, 1957)
   Lochan a'Bhuilg Bhith, 2 mls. SE of Oban. NM 872276

6. Oban 2 (Donner, 1957)
   Small pond near Pulpit Hill, SE side of Sound of Kerrera. NM 851292

7. Garral Hill (Donner, 1957; Godwin and Willis, 1959)
   4 mls. N of Keith, Banffshire. NJ 444551

8. (See 'Note' below)

9. Loch Droma (Kirk and Godwin, 1963)
   Through valley of Dirrie More, between Loch Broom and Glascarnoch (4°56'W. 57°44'N).

10. Loch Kinord (Vasari and Vasari, 1968; Vasari, 1977)
    34 km W of Loch of Park. NO 435997

11. Loch of Park (Vasari and Vasari, 1968; Vasari, 1977)
    2 km W of Park Station, Aberdeenshire. NO 772988

12. Culhorn Mains (Moar, 1969a)
    Culhorn Mains Farm, 3 km SE of Stranraer, Wigtownshire. NX 085593

13. Little Lochans (Moar, 1969a)
    Little Lochans Farm, 3 km SSE of Stranraer, Wigtownshire. NX 076578

14. Bigholm Burn (Moar, 1969a)
    Valley of Bigholm Burn, 6 km W of Langholm, Dumfriesshire. NY 316812

15. Chirmorrie Farm (Moar, 1969a)
    8 km SE of Barhill, Wigtownshire. NX 217769

16. Creebank (Moar, 1969a)
    Ayrshire-Wigtownshire border *ca.* 3 km N of Bargrennan. NX 346773

17. High Drummore Farm (Moar, 1969a)
    NX 385617

18. Loch Hempton (Moar, 1969a)
    NX 307457

19. Yesnaby Head (Moar, 1969b)
    Orkney Islands. HY 237152

20. Corstorphine (Newey, 1970)
    W end of Edinburgh. NT 214727

21. Shieldaig (Petrie, 1970)
    4 km due S of Shieldaig, Wester Ross.

22. Abernethy Forest (Birks, H.H., 1970; Vasari, 1977)
    Between Loch Garten and Loch Mallachie, Inverness-shire.
    NH 967175

23. Brimmond Hill (Durno, 1970)
    Near Aberdeen. NJ 849096

24. Loch Sionascaig (Pennington and Lishman, 1971; Pennington *et al*., 1972)
    Wester Ross.

25. Loch Tarff (Pennington *et al*., 1972)
    Small lake on moorland above Loch Ness.

26. Loch Craggie (Pennington *et al*., 1972)
    Between the drainage basins of the Rivers Kirkaig and Oykell, Wester Ross.

27. Loch Borralan (Pennington *et al*., 1972)
    Due west of main Highland watershed, on border between Sutherland and Ross-shire.

28. Tynaspirit (Lowe, this thesis)
    2 km SE of Callander. NN 665048

29. Cambusbeg (Lowe, this thesis)
    2 km SE of Callander. NN 658051

30. Amulree (Lowe, this thesis)
    3 km S of Amulree, 12 km due N of Crieff. NN 895338

31. Tirinie (Walker, 1974)
    3 km NE of Blair Atholl, in Glen Fender, Perthshire. NN 889678

32. Corrydon (Walker, 1974)
    3.5 km SE of Spittal of Glenshee, Perthshire. NO 132674

33. Roineach Mhor (Walker, 1974)
    Glen Clova, Angus, 25 km NW of Forfar. NO 331728

34. Blackness (Walker, 1974)
    25 km NW of Brechin, in Glen Esk, Angus. NO 463786

35. Loch Etteridge (Walker, 1974; Sissons and Walker, 1974)
    7.5 km SW of Newtonmore, Inverness-shire. NN 688929

36. Straloch (J.H. Dickson, unpublished)
    Kettle hole near Straloch, Strathardle, Perthshire. NO 041693

37. Loch Meodal (Birks, 1973)
    16 km S of Broadford, 8 km N of Ardavasar, I. of Skye. NG 656112

38. Loch Fada (Birks, 1973)
6 km N of Portree, 5 km S of the Storr, I. of Skye. NG 494494

39. Loch Mealt (Birks, 1973)
20 km N of Portree, 3.5 km SSE of Staffin, I. of Skye. NG 505650

40. Loch Cill Chriosd (Birks, 1973)
4 km SW of Broadford, 3 km E of Loch Slapin, I. of Skye. NG 605203

41. Lochan Coir a'Ghobhainn (Birks, 1973)
3 km SSE of Glenbrittle House, 4 km SW of the summit of Sgurr Sgumain. NG 417183

42. Loch Duntulm (H.J.B. Birks, unpublished)
N coast of I. of Skye. NG 414743

43. Din Moss (Switsur and West, 1973)
Roxburghshire. NT 805315

44. Loch of Leys (A.R. Gunson, unpublished)
2 km NNE of Banchory, Aberdeenshire. NO 772988

45. Loch Davon (A.R. Gunson, unpublished)
2 km NW of Dinnet, Aberdeenshire. NJ 441004

46. Tarves (A.R. Gunson, unpublished)
5 km NNE of Old Meldrum, Aberdeenshire. NJ 832318

47. Loch Builg (Clapperton et al., 1975)
13 km NE of Braemar, in Banffshire. NJ 189035

48. Loch a' Chnuic (O'Sullivan, 1974)
7 km SE of Nethy Bridge, Inverness-shire. NJ 045143

49. Loch Damph (M. Jackes, unpublished)
Near Loch Coultrie, SE of southernmost shore of Loch Damph. NG 866463

50. White Hills (S.E. Durno, unpublished)
3 km NE of Alness, Easter Ross NH 671706

51. North Cadboll (S.E. Durno, unpublished)
Due N of Hilton of Cadboll, Easter Ross. NH 876787

52. Ulbster Moss (S.E. Durno, unpublished)
Caithness. ND 336431

53. Loch of Winless (H.J.B. Birks, unpublished)
Caithness. ND 295545)

54. Loch Assynt (H.J.B. Birks, unpublished)
Sutherland

55. An Druim (H.J.B. Birks, unpublished)
By Loch Eriboll, Sutherland. NC 435568

56. Cam Loch (Pennington, 1975)
Sutherland.

57. Loch Stack (W. Pennington, unpublished)
Sutherland.

58. The Whitlaw Mosses (J. Webb, unpublished)
Small basin in undulating topography on Selkirk/Roxburghshire border. NT 518293.

NOTE

Site number 8 has been deleted from this list and from Fig. 35. This referred to a section at the Burn of Benholm, Kincardineshire (Donner, 1961), the original interpretation of which is now regarded by the author as questionable.

APPENDIX 2

Contamination caused by the use of the Hiller peat sampler

References have been made in chapters 2, 4 and 5 to lithostratigraphic and biostratigraphic distortion in records of sediments obtained by Hiller sampler. The main cause of biostratigraphic distortion is the contamination of older deposits by younger material that has adhered to the chamber of the Hiller during sampling. The data presented below illustrate the problem of contamination of pollen spectra. The actual pollen counts recorded for levels close to the main boundary between minerogenic and organic sediments at Amulree and Mollands and based on samples collected by Hiller sampler and subsequently by piston corer are compared. For brevity, the pollen counts have been generalised

(i) Amulree

	Abbey piston corer (Fig. 22)					Hiller sampler (Fig. 20)				
Level (cm below surface)	889	894	899	904	909	820	825	835	840	845
sum land pollen	200	200	200	200	200	362	406	304	241	211
sum AP	25	46	46	40	31	48	86	60	29	20
Betula	8	20	24	20	11	39	82	45	13	6
Pinus	17	26	22	20	20	9	3	15	16	13
Ulmus							1			1
Salix	12	3	4	6	3	33	20	21	12	6
Empetrum	2	1	1		1	17	24	18	3	1
Juniperus	6	9	2	4	3	38	50	45	19	10
Corylus						1	7	6		
sum herbaceous pollen	155	141	147	150	162	225	220	155	178	174
Gramineae	30	32	23	32	20	95	94	42	37	44
Cyperaceae	65	45	26	41	50	66	70	48	60	57

(ii) Mollands

	Abbey piston corer (Fig. 25)				Hiller sampler (Fig. 23)			
Level (cm below surface)	724	726	728	729.5	723	728	733	743
sum land pollen	100	100	100	100	311	300	300	300
sum AP	14	20	10	27	131	43	55	101
Betula	9	4	2	1	127	29	46	95
Pinus	5	16	8	26	4	8	9	5
Quercus					2	3		1
Alnus						3		
Populus					3			
Salix	5	7	1	1	13	24	13	9
Empetrum						13	3	
Betula nana	3	2						
Ericaceae					4	6	4	5
Juniperus	3		1	1	12	11	18	14
Corylus					21	6	13	24
sum herbaceous pollen	75	72	88	71	130	197	194	147
Gramineae	21	19	29	21	62	116	108	86
Cyperaceae	20	32	30	18	27	42	28	27

The horizons compared at both Amulree and Mollands are believed to be more or less contemporaneous (chapters 4 and 7) yet significant differences can be seen in the pollen records. At Amulree the numbers of grains of shrubs are greatly exaggerated in the counts based on samples collected by Hiller, and Corylus and Ulmus grains are recorded for these sediments though both genera are not recorded at all for sediments collected by Abbey piston corer. The pollen counts from Mollands based on samples collected by piston corer are quite consistent, with the exception of the record of Pinus grains. The counts based on samples collected by Hiller for comparable levels show clear exaggeration of Betula, Salix and Juniperus, and the following taxa are recorded that are not recorded for the sediments collected by piston corer: Quercus, Alnus, Populus, Corylus and Ericaceae.

The exaggeration at both sites of pollen of Salix, Empetrum, Juniperus and Corylus in sediments that occur immediately below the organic Flandrian deposits indicates that pollen grains have been carried down from early Flandrian organic horizons, horizons that are pollen-rich with these shrub genera well represented. Probably a thin film of organic material has adhered to the outside of the Hiller chamber, and this organic material must have been incorporated into the lower minerogenic sediments during the turning of the chamber. Organic staining was found on some minerogenic samples after inspection in the laboratory, and where found the samples were discarded. The samples analysed for Figs. 20 and 23 discussed above were inspected before analysis and no staining was detected. The amount of contamination in volumetric terms must have been exceedingly small, but the distortion of the pollen spectra is nevertheless severe.

Other instances of contamination have been referred to in the text, where it has been established that this is a common problem in pollen spectra from Lateglacial or Loch Lomond Stadial/Flandrian transition minerogenic sediments where the Hiller sampler has been employed. In presenting a detailed history of vegetation during the Lateglacial, especially in attempts to establish the early history of such genera as Corylus and Juniperus, it would seem imperative to recognise the type of samplers employed, and, where possible, to avoid the use of data based on samples collected by Hiller corer.

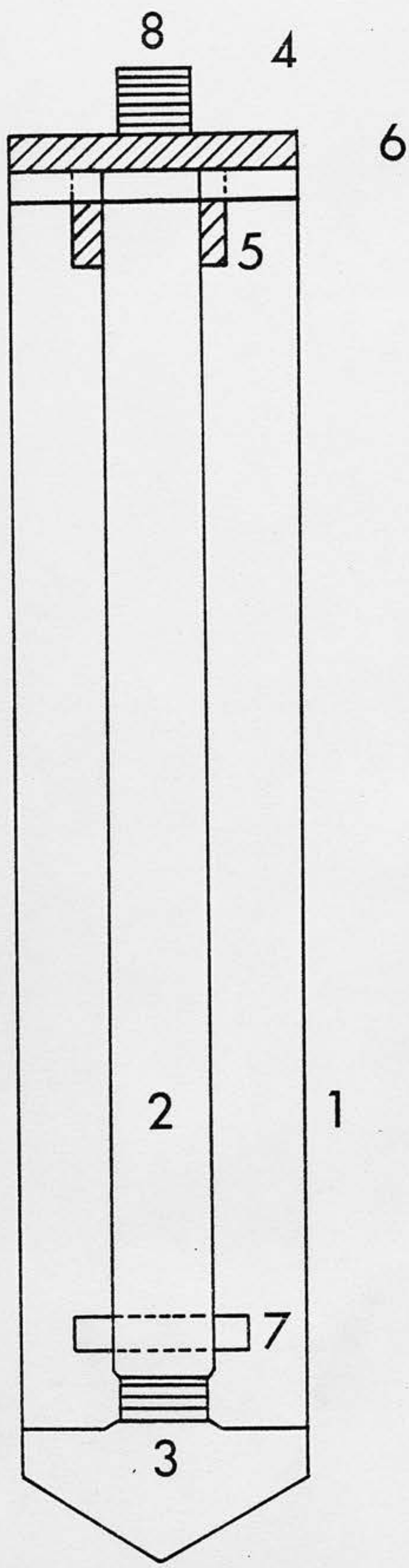
Though sampling was unsuccessful at two sites when using the Russian sampler (Tynaspirit and Cambusbeg), those cores that were recovered revealed signs of significant lithostratigraphic distortion. It would appear that stratigraphic distortion and contamination are serious problems where use is made of an auger that samples on the principle of rotating a moveable chamber. Sampling by Hiller or Russian corers involves the collection of material that has already been disturbed (and contaminated by younger material that has adhered to the outside of the chamber) by the passage of the chamber through the sediments prior to sampling. This problem is most severe where a relatively narrow chamber is employed (see Fig. 23 and data above). Stratigraphic disturbance and contamination are minimal where sampling is direct, using a piston chamber of 5.0 - 6.0 cm diameter with a relatively thin casing and sharp cutting edge.

APPENDIX 3

The Abbey Piston Corer

The Abbey piston corer is a hand-operated corer that operates on the Dachnowski principle, but significant modifications have been incorporated that make it superior to the original Dachnowski model. The most important feature of the corer is that the sampling chamber can be completely dismantled, thus ensuring thorough cleaning between samplings. The cores that are retrieved are thus virtually free from contamination, and they are sufficiently large to allow for pollen and macrofossil studies, as well as for sedimentological analyses and radiocarbon dating. The chamber of the Abbey corer was designed by Abbey Tool and Guage, and the chamber plus all necessary attachments can be obtained from Mr. A.G. Reid, Abbey Tool and Guage, Spylaw Road, Kelso, Roxburghshire, Scotland.

The Abbey corer (Fig. 37) consists of a steel chamber 66 cm in length, with an external diameter of 5.6 cm and an internal diameter of 5 cm (1). The centre rod (2) is made of solid steel and is 3 cm in diameter. The nose cone (3) is also of solid steel and is detachable from the centre rod. The top plate (4) is attached to the centre rod by steel wing-pieces (5), and the latter enable the entire sampling chamber to be turned in sediments when closed. The locking plate (6) screws into the top of the sampling chamber, and is easily removed thus allowing the chamber to be cleaned out thoroughly from both ends. A solid steel bar (7) is fastened through the centre rod immediately above the nose cone. When the centre rod is withdrawn and turned through 90^{0}, downward progress of the sampler can be effected by the pressure of (7) on the locking plate (6). The centre rod is attached to the extension rods by a robust thread connection (8). The extension rods themselves are made of mild steel, are one metre in length and have thread connections. The T-bar handle which screws onto the rods is specially strengthened. Auger fitments are available that allow penetration through particularly coarse horizons to enable subsequent sampling in underlying softer deposits.



THE ABBEY PISTON CORER

1 Sampling chamber
2 Centre rod
3 Nose cone
4 Top plate
5 Wing pieces
6 Locking plate
7 Steel bar
8 Thread connection

FIGURE 37 The Abbey piston corer.

APPENDIX 4

The nature of peat-filled depressions between hummocks in areas of hummocky moraine

The evidence of numerous test-bores in areas of hummocky moraine in southern Perthshire has revealed that completely enclosed hollows within deposits of hummocky moraine are exceedingly rare. In southern Perthshire the following areas were investigated in detail: upper Glen Almond, the area to the south of Ben Vorlich and Forest of Glenartney, the Comrie-Crieff region and the glens to the south of Ben Chonzie. Aerial photographic analysis revealed a number of possible sites where apparently deep mires had developed, but almost invariably field inspection proved these to be either very shallow or to relate to channel systems now buried by the peat. Where channels exist, drainage would not have been prevented following deglaciation, and thus such sites are of no value in an investigation aiming to date the age of deglaciation. Only two sites were discovered within the Loch Lomond Readvance ice limits, Mollands and Glenturret, the latter site providing the only example of a relatively deep kettle hole discovered within the well-formed hummocky moraine deposits of southern Perthshire.

Other research by the author has included systematic sub-surface boring in the excellent hummocky moraines of the 'Valley of the Hundred Hills' by Glen Torridon (Lowe, 1970) and in the deposits of the series of terminal moraines in the Spean and Treig valleys (unpublished) described in Sissons (1976a). In the former area only one enclosed depression was discovered, and in the latter two enclosed depressions (440 and 540 cm deep) were discovered. In both areas large tracts of peatland between the numerous hummocks have covered minor hummocks and inter-connecting channels that descend to the middle of the respective valleys. Early Flandrian deposits in the base of the three kettle holes discovered are indicated by pollen analysis.

In the north-western part of Rannoch Moor an area of hummocky moraine deposits some 11 km^2 has been thoroughly examined for possible enclosed basin deposits (Lowe and Walker, unpublished). This has involved test-boring in all depressions between morainic mounds and ridges, for, as in those areas referred to above, deep enclosed depressions are no longer obvious in the landscape as a result of widespread peat accumulations. Sixty-four test-bores in the area between the Kingshouse Hotel, Black Corries and Creag Dhubh revealed a general peat cover of about 3.0 to exceptionally 3.5 m. The peat has accumulated between mounds and ridges obscuring, in the main, a system of open channels, but also infilling three enclosed depressions. From one of these depressions early Flandrian and late Loch Lomond Stadial deposits have been proved by pollen analysis and radiocarbon dating (Lowe and Walker, in press). This study formed part of a more comprehensive study of Rannoch Moor, in which hundreds of hand-operated test-bores have been made in the areas of continuous spreads of hummocky moraine around Rannoch Station, to the west of Loch Ossian, the Black Mount area, the valley of the Water of Tulla, and the area to the west of Loch Tulla. Outside the Rannoch basin the areas around Tyndrum and in the Leanachan Forest (south of Spean Bridge) have also been investigated.

In all of the areas of hummocky moraine referred to above enclosed depressions are quite rare, and the depressions between hummocks and ridges are predominantly related to open channel systems that permit free drainage (in places the sub-peat down-slope drainage is evident) towards the middle of the valleys, or, in parts of Rannoch Moor, towards the large lochs. It is tempting to suggest that the comparative rarity of kettles in Loch Lomond Readvance deposits relates directly to the manner of deglaciation, implying, for instance, rapid deglaciation as a consequence of rapid climatic improvement. On the other hand the detailed morphology of the Loch Lomond Readvance deposits may relate directly to major topographic situations. Thus, for instance, deep kettles occur in the kames and terraces of Loch Lomond Stadial age in the lower Treig-Spean Valley area (Sissons, 1976a). The nature of the sub-peat ("original") morphology of Loch Lomond Readvance deposits might prove worthy of further and more comprehensive studies.

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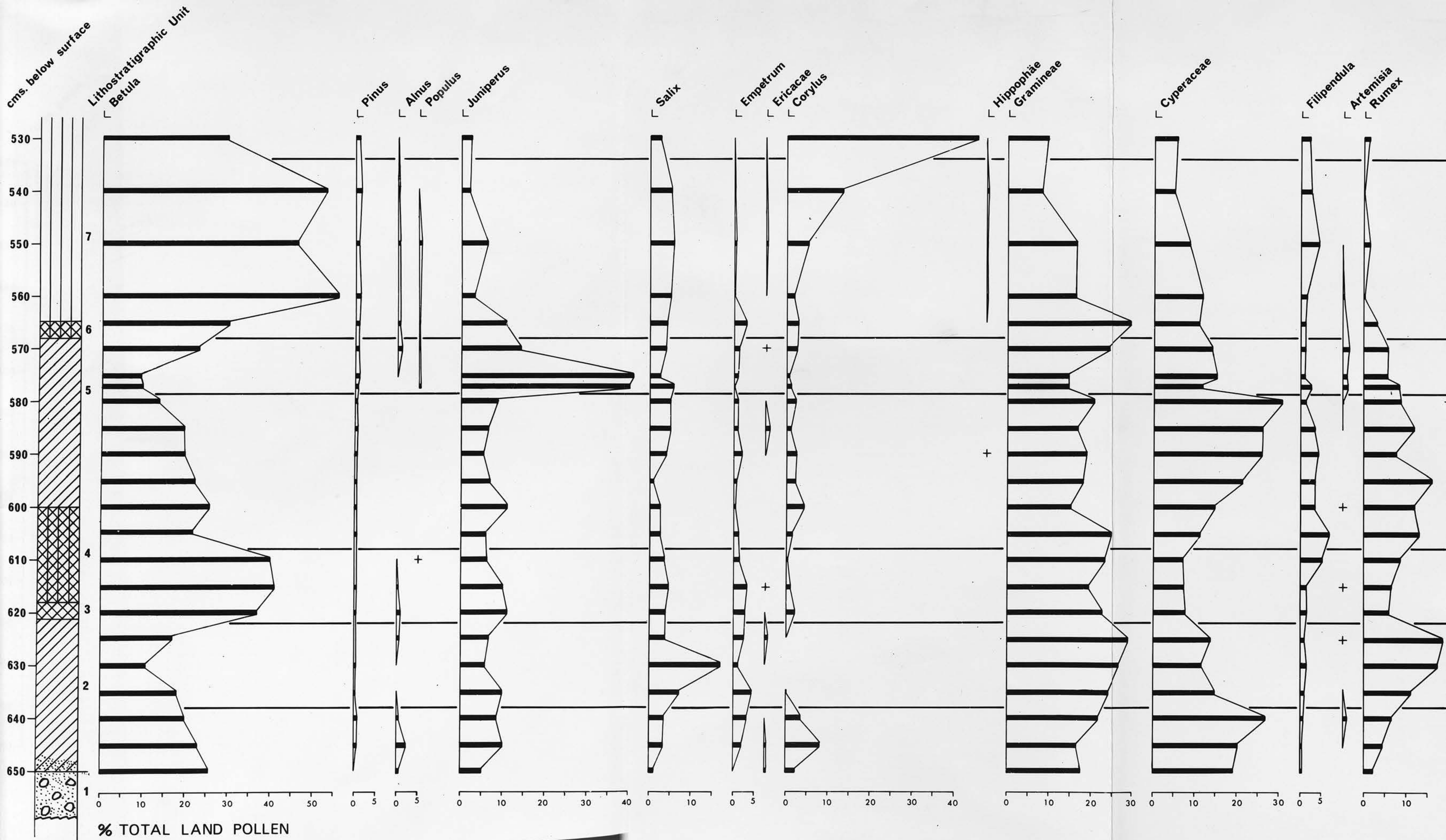


FIGURE 15 TYNASPIRIT 1: Lateglacial-early Flandrian pollen diagram. 'Herbaceous Pollen' excludes Gramineae and Cyperaceae.

Filipendula
Artemisia
Rumex
Chenopodiaceae
Ranunculaceae
Rosaceae
Galium
Dryas
Caryophyllaceae
Compositae
Thalictrum
Umbelliferae
Urtica
Polygonaceae
Armeria
Epilobium
Valeriana
Saxifragaceae
Plantago
Cruciferae
Helianthemum
% Total Herbaceous Pollen
Σ Land Pollen
Spores
Selaginella
Myriophyllum
Potamogeton
Sparganium
Deteriorated Pollen
Pollen Zone (Local)
Correlation
526
281
319
263
322
327
323
317
329
327
339
216
316
306
315
309
314
210
213
312
232
182
165
T1g
T1f
T1e
T1d
T1c
T1b
T1a
V
IV
III – IV
III
II
I
FLANDRIAN
STADIAL
INTERSTADIAL

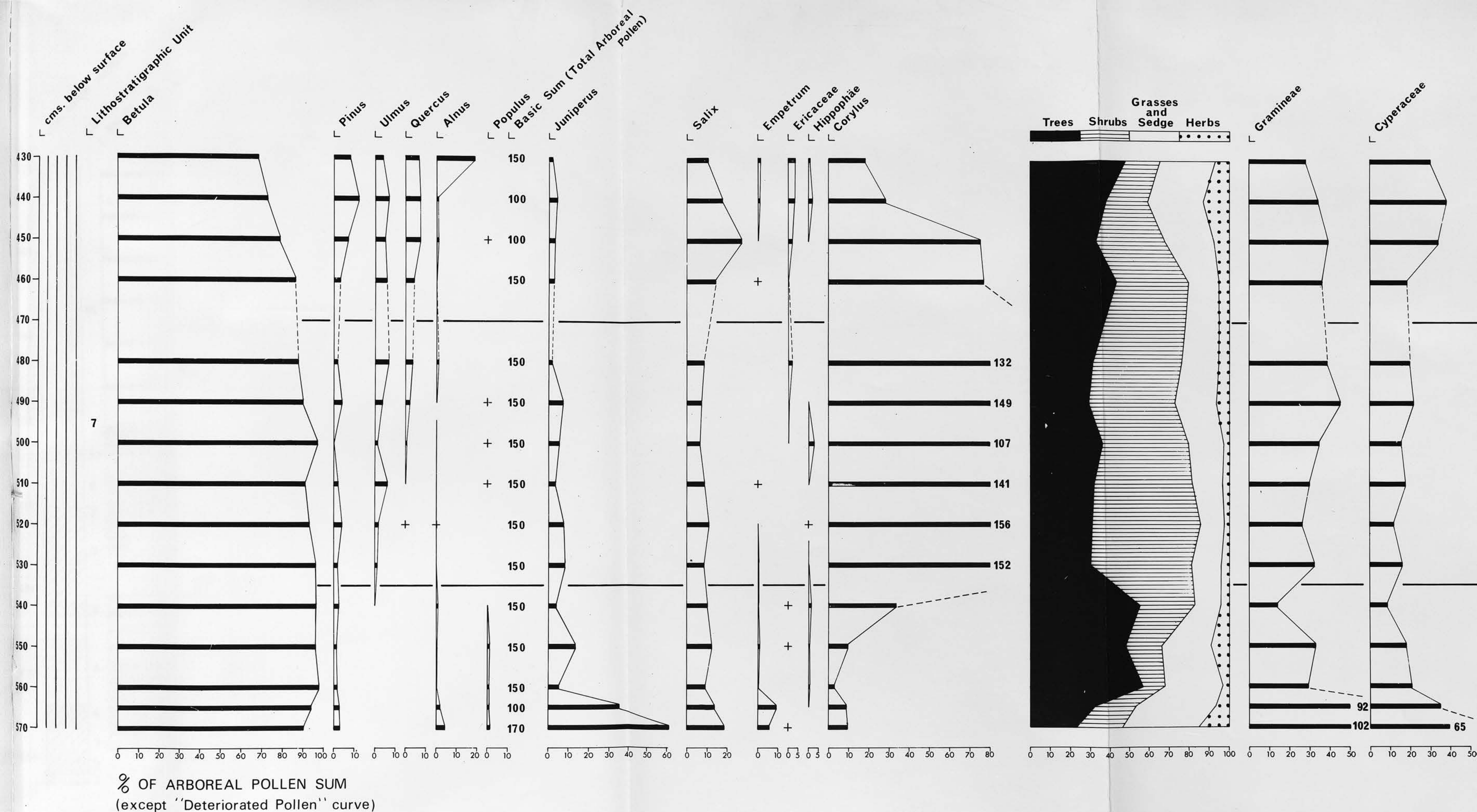
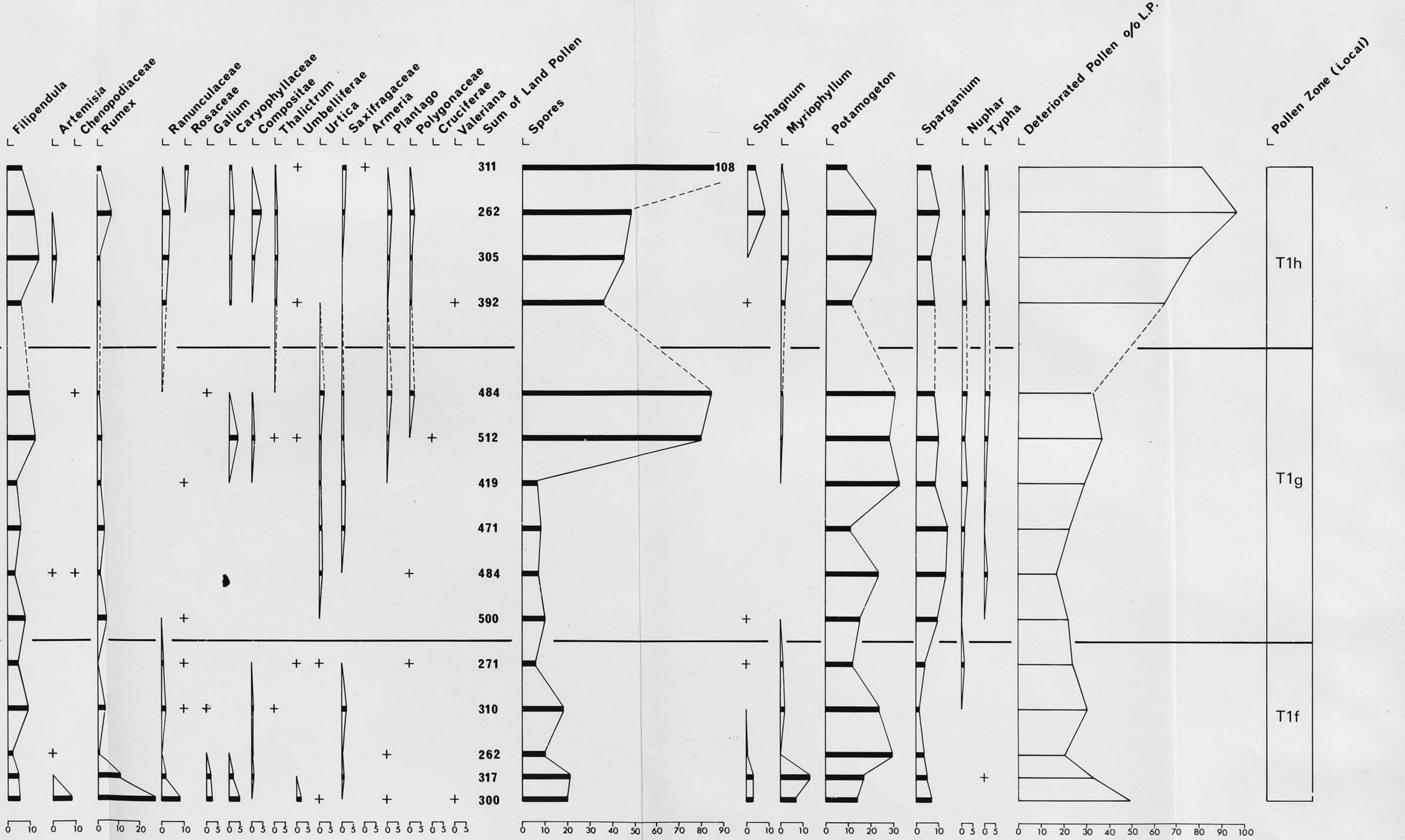


FIGURE 16 TYNASPIRIT 1: early Flandrian pollen diagram.


Filipendula
Artemisia
Chenopodiaceae
Rumex
Ranunculaceae
Rosaceae
Galium
Caryophyllaceae
Compositae
Thalictrum
Umbelliferae
Urtica
Saxifragaceae
Armeria
Plantago
Polygonaceae
Cruciferae
Valeriana
Sum of Land Pollen
Spores
Sphagnum
Myriophyllum
Potamogeton
Sparganium
Nuphar
Typha
Deteriorated Pollen o/o L.P.
Pollen Zone (Local)
311
262
305
392
484
512
419
471
484
500
271
310
262
317
300
108
T1h
T1g
T1f

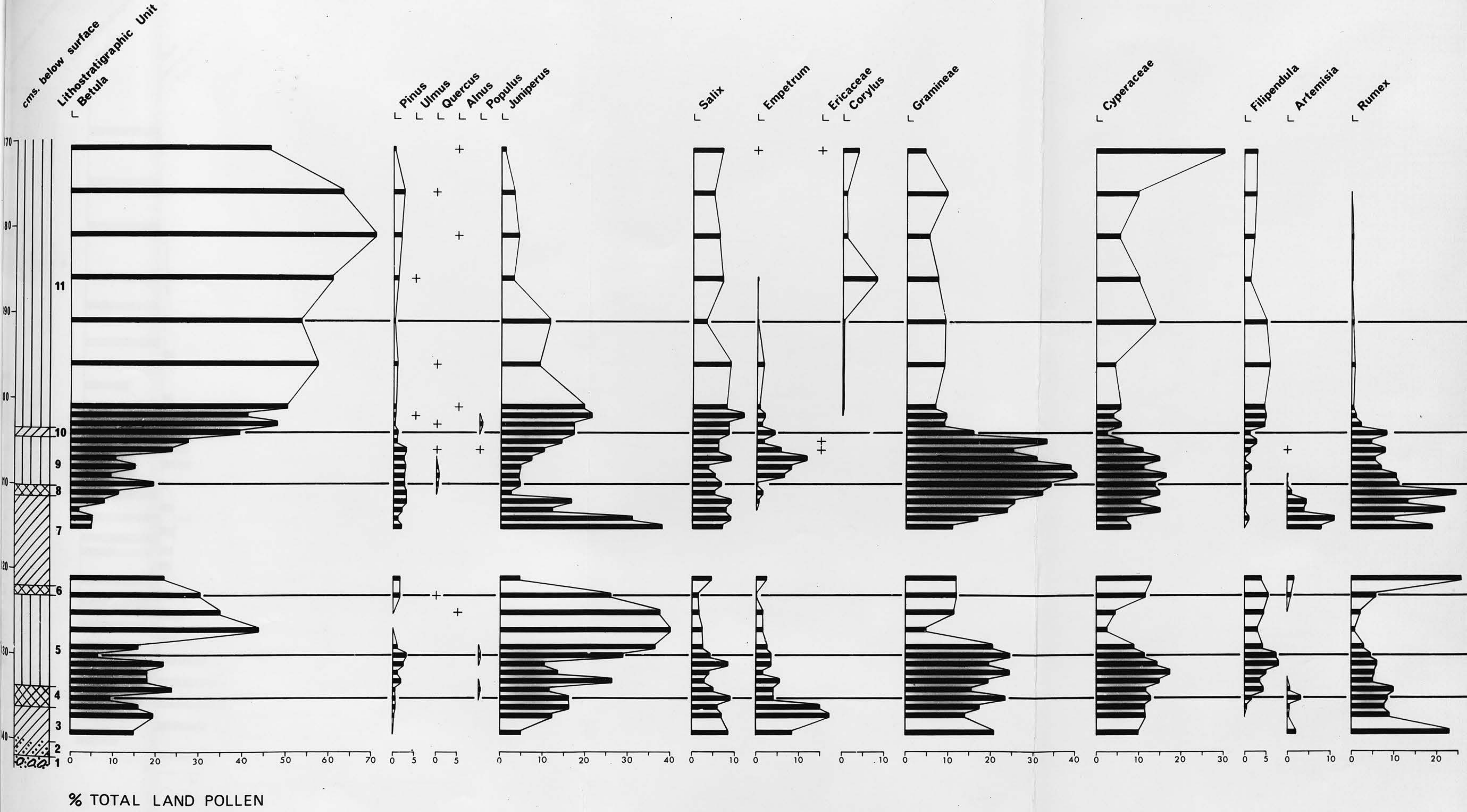


FIGURE 17 TYNASPIRIT 2: Lateglacial-early Flandrian pollen diagram and radiocarbon dates (years B.P.).

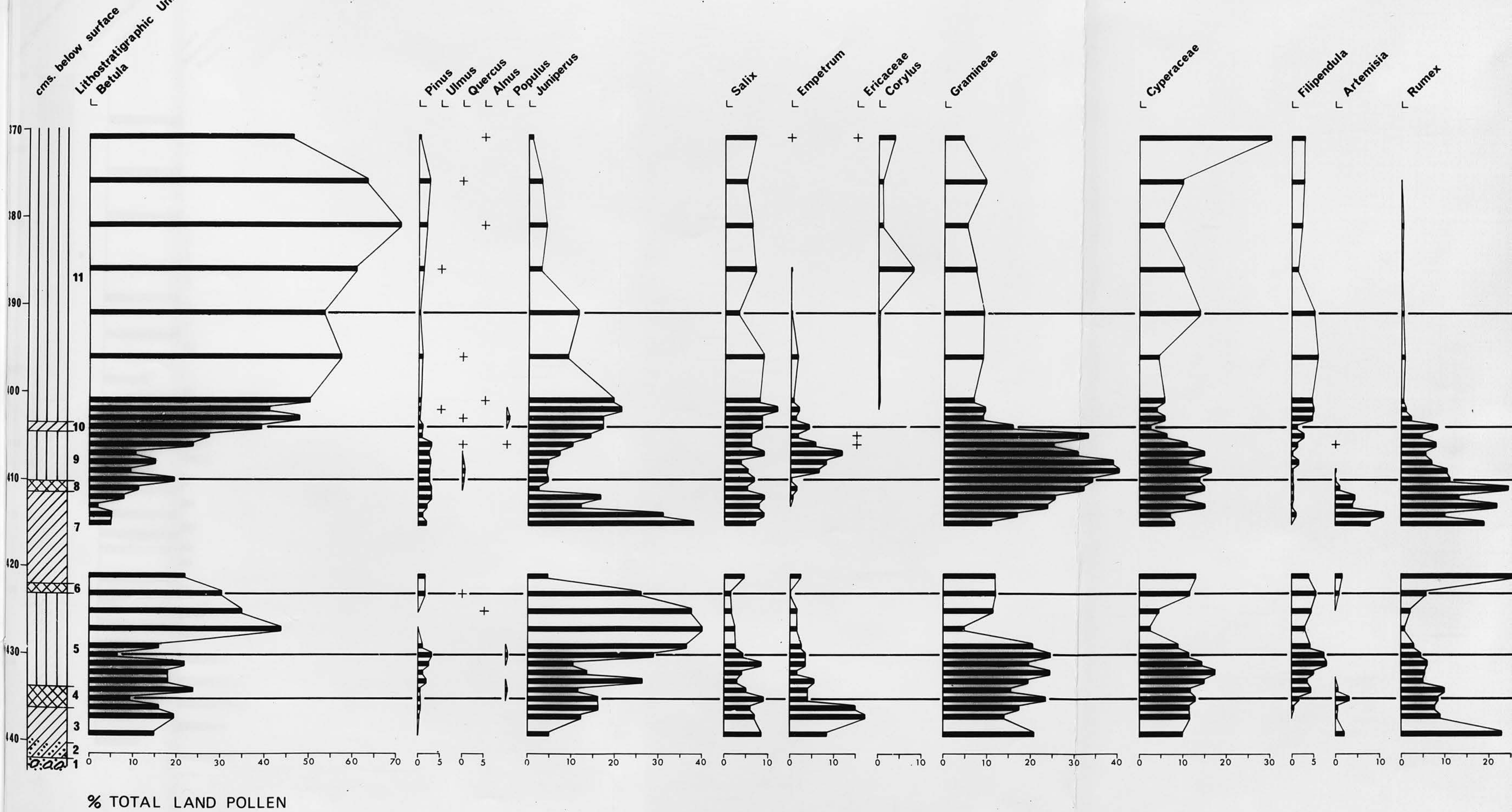
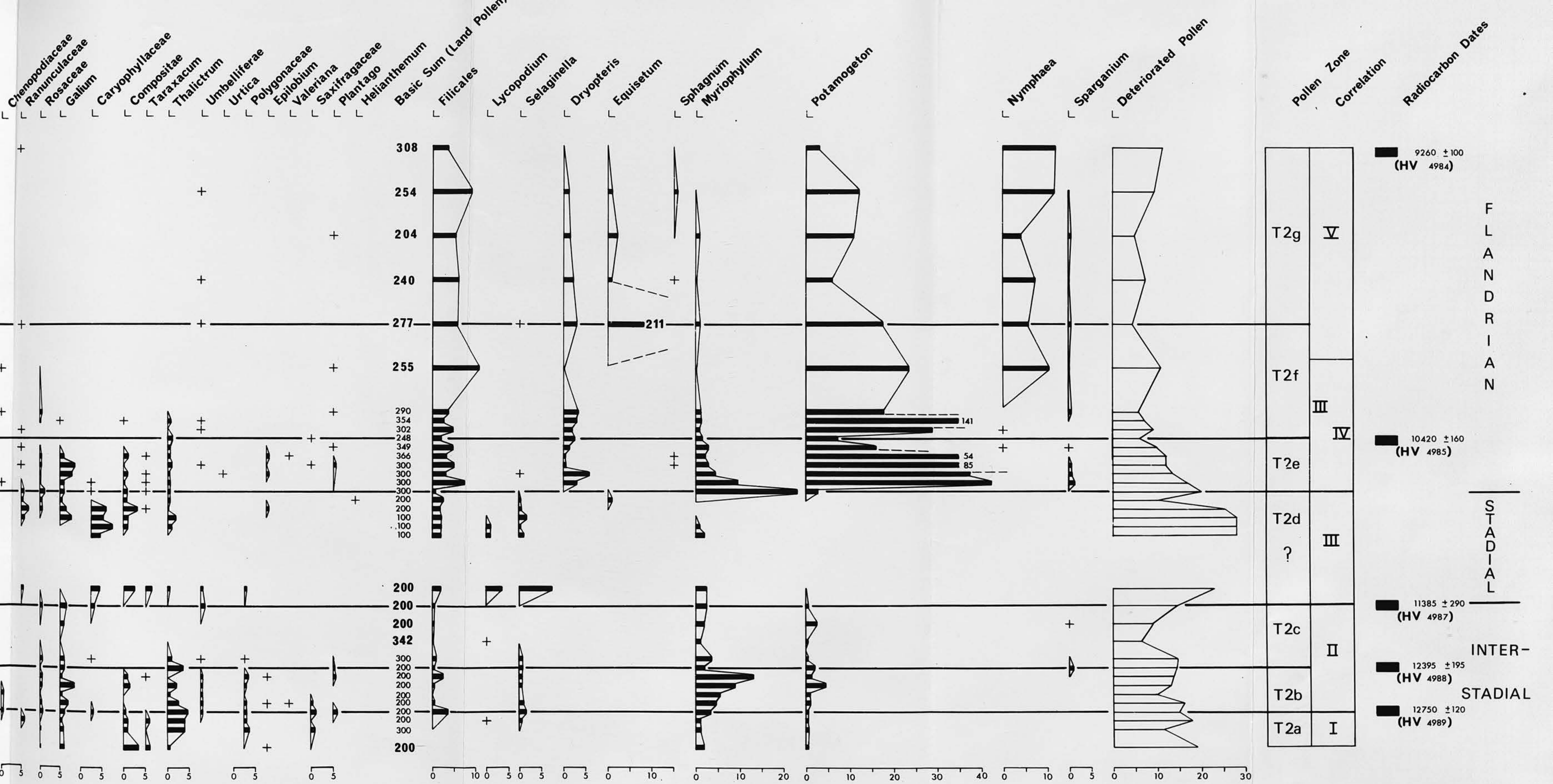
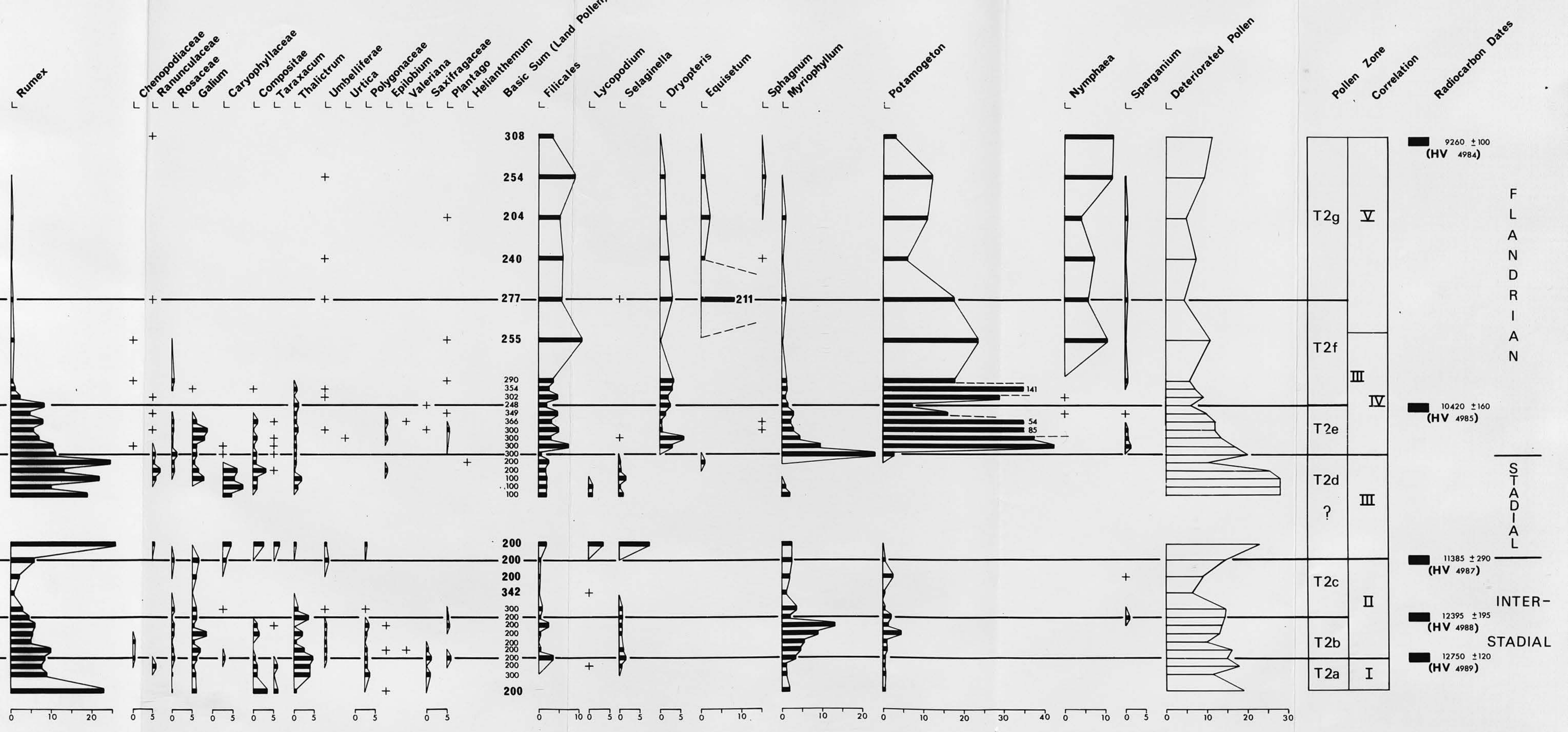


FIGURE 17 TYNASPIRIT 2: Lateglacial-early Flandrian pollen diagram and radiocarbon dates (years B.P.).

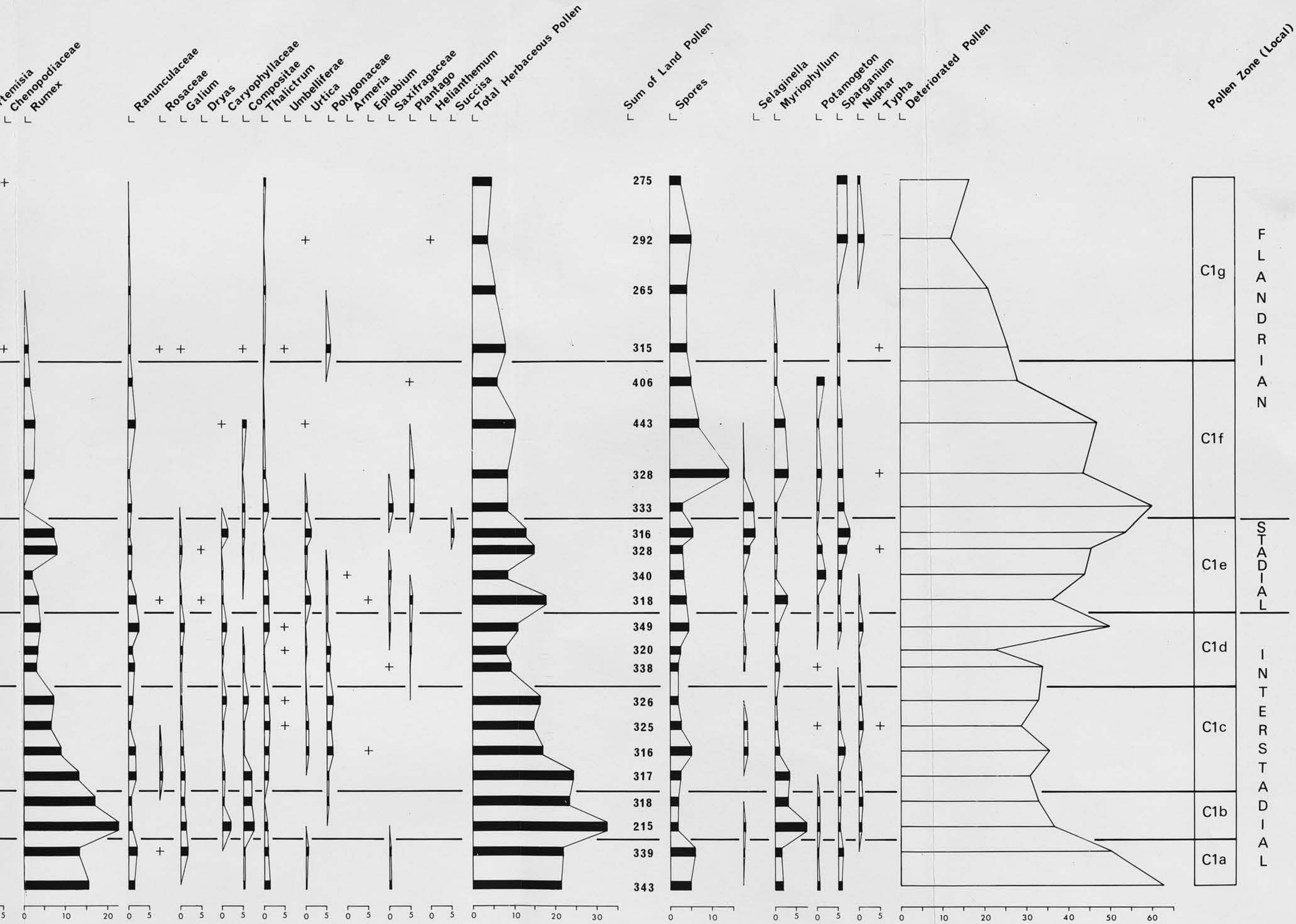


Chenopodiaceae
Ranunculaceae
Rosaceae
Galium
Caryophyllaceae
Compositae
Taraxacum
Thalictrum
Umbelliferae
Urtica
Polygonaceae
Epilobium
Valeriana
Saxifragaceae
Plantago
Helianthemum
Basic Sum (Land Pollen)
Filicales
Lycopodium
Selaginella
Dryopteris
Equisetum
Sphagnum
Myriophyllum
Potamogeton
Nymphaea
Sparganium
Deteriorated Pollen
Pollen Zone
Correlation
Radiocarbon Dates
308
254
204
240
277
211
255
290
354
302
248
349
366
300
300
300
300
200
200
100
100
100
200
200
200
342
300
200
200
200
200
200
200
200
300
200
141
54
85
T2g
T2f
T2e
T2d
?
T2c
T2b
T2a
V
III
IV
III
II
I
9260 ± 100
(HV 4984)
10420 ± 160
(HV 4985)
11385 ± 290
(HV 4987)
12395 ± 195
(HV 4988)
12750 ± 120
(HV 4989)
FLANDRIAN
STADIAL
INTER-
STADIAL
0 5
0 5
0 5
0 5
0 5
0 5
0 5
0 5
0 10
0 5
0 5
0 5
0 10
0 10 20
0 10 20 30 40
0 10
0 5
0 10 20 30



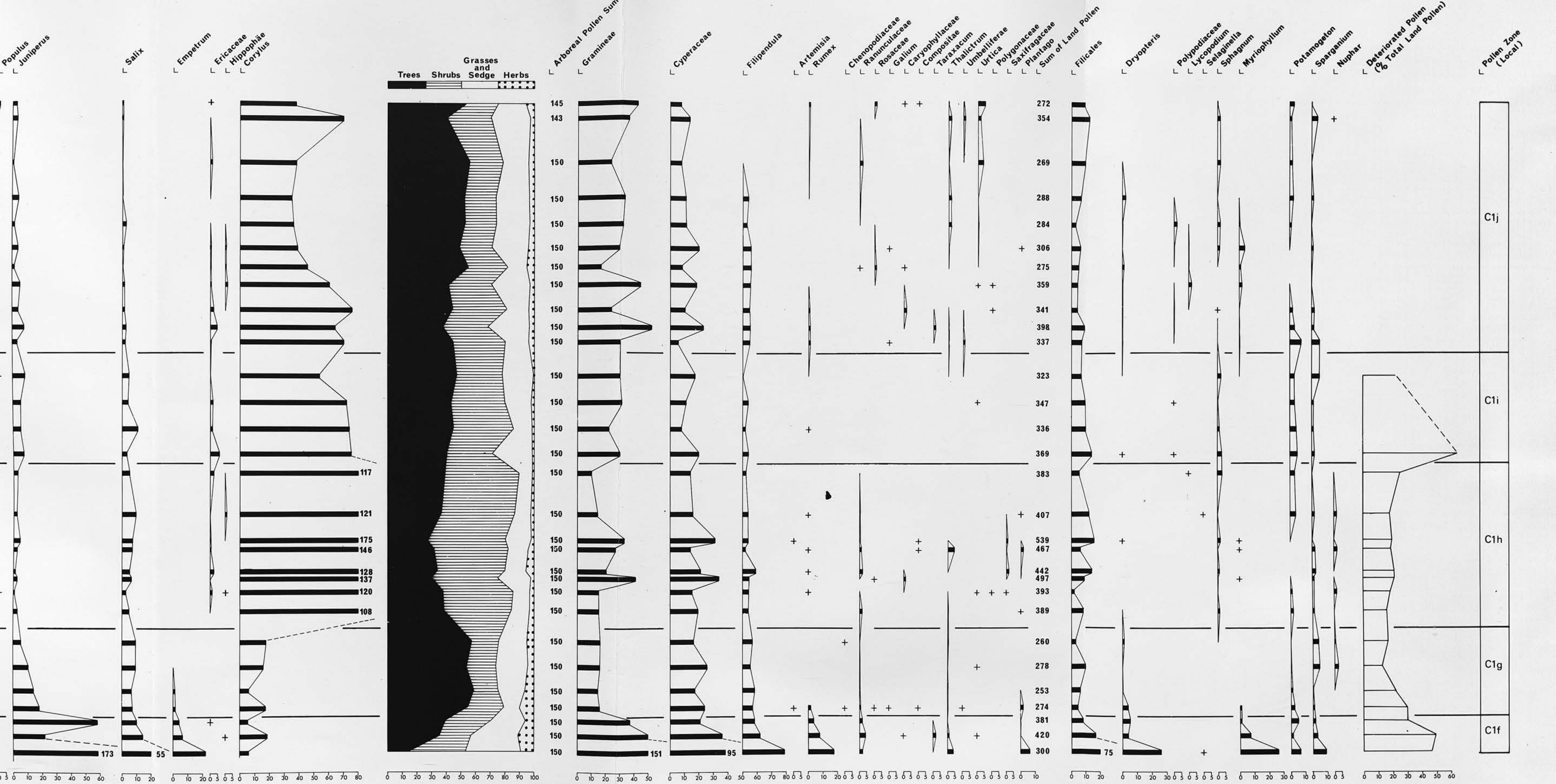
Rumex
Chenopodiaceae
Ranunculaceae
Rosaceae
Galium
Caryophyllaceae
Compositae
Taraxacum
Thalictrum
Umbelliferae
Urtica
Polygonaceae
Epilobium
Valeriana
Saxifragaceae
Plantago
Helianthemum
Basic Sum (Land Pollen)
Filicales
Lycopodium
Selaginella
Dryopteris
Equisetum
Sphagnum
Myriophyllum
Potamogeton
Nymphaea
Sparganium
Deteriorated Pollen
Pollen Zone
Correlation
Radiocarbon Dates
T2g
T2f
T2e
T2d
?
T2c
T2b
T2a
V
IV
III
II
I
9260 ±100 (HV 4984)
10420 ±160 (HV 4985)
11385 ±290 (HV 4987)
12395 ±195 (HV 4988)
12750 ±120 (HV 4989)
FLANDRIAN
STADIAL
INTER-STADIAL

<u>FIGURE 18</u> CAMBUSBEG: Lateglacial-early Flandrian pollen diagram.
'Total Herbaceous Pollen' excludes Gramineae and Cyperaceae.



Chenopodiaceae
Rumex
Ranunculaceae
Rosaceae
Galium
Dryas
Caryophyllaceae
Compositae
Thalictrum
Umbelliferae
Urtica
Polygonaceae
Armeria
Epilobium
Saxifragaceae
Plantago
Helianthemum
Succisa
Total Herbaceous Pollen
Sum of Land Pollen
Spores
Selaginella
Myriophyllum
Potamogeton
Sparganium
Nuphar
Typha
Deteriorated Pollen
Pollen Zone (Local)
275
292
265
315
406
443
328
333
316
328
340
318
349
320
338
326
325
316
317
318
215
339
343
C1g
C1f
C1e
C1d
C1c
C1b
C1a
FLANDRIAN
STADIAL
INTERSTADIAL

FIGURE 19 CAMBUSBEG: Pollen diagram through consolidated Flandrian sediments.



consolidated

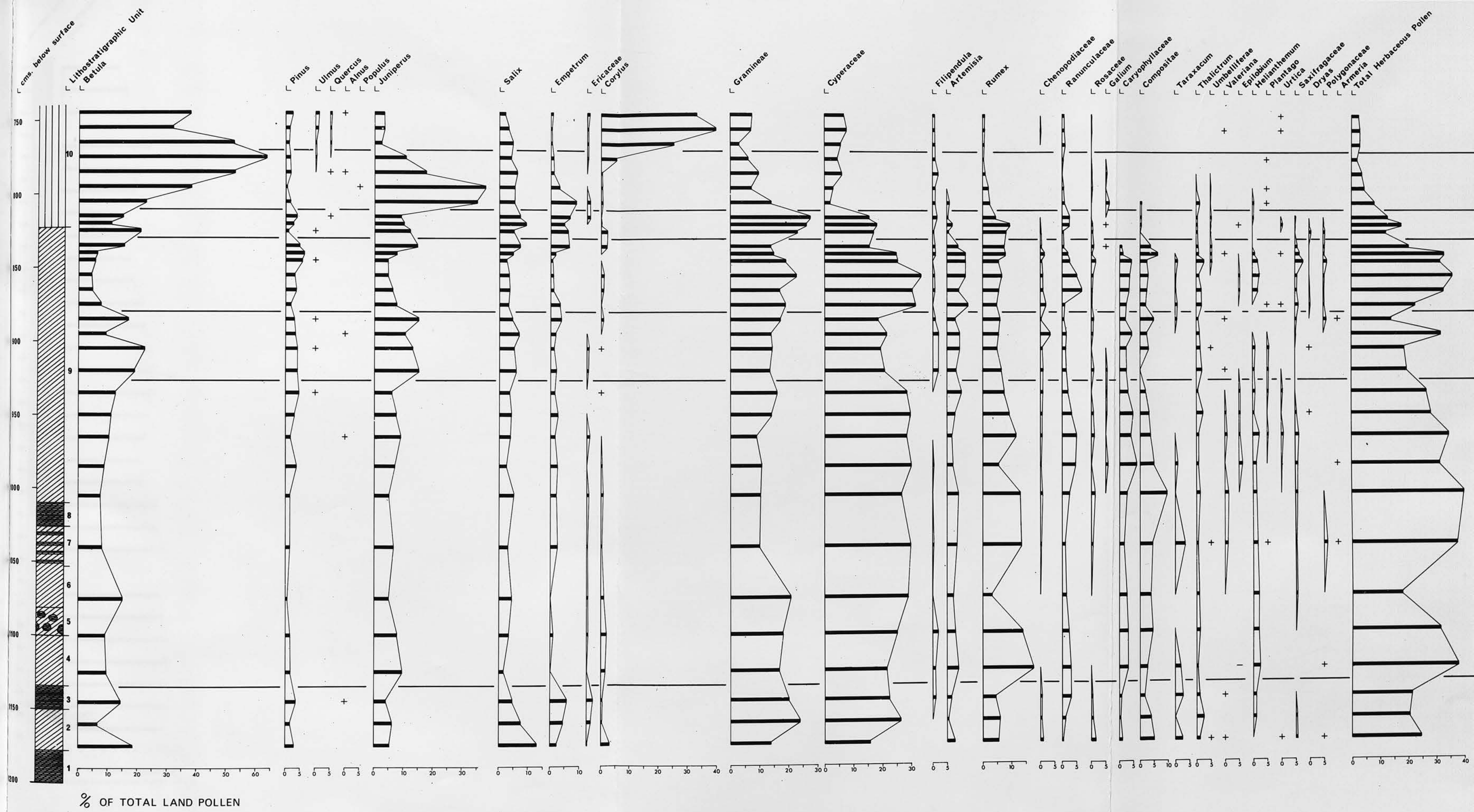
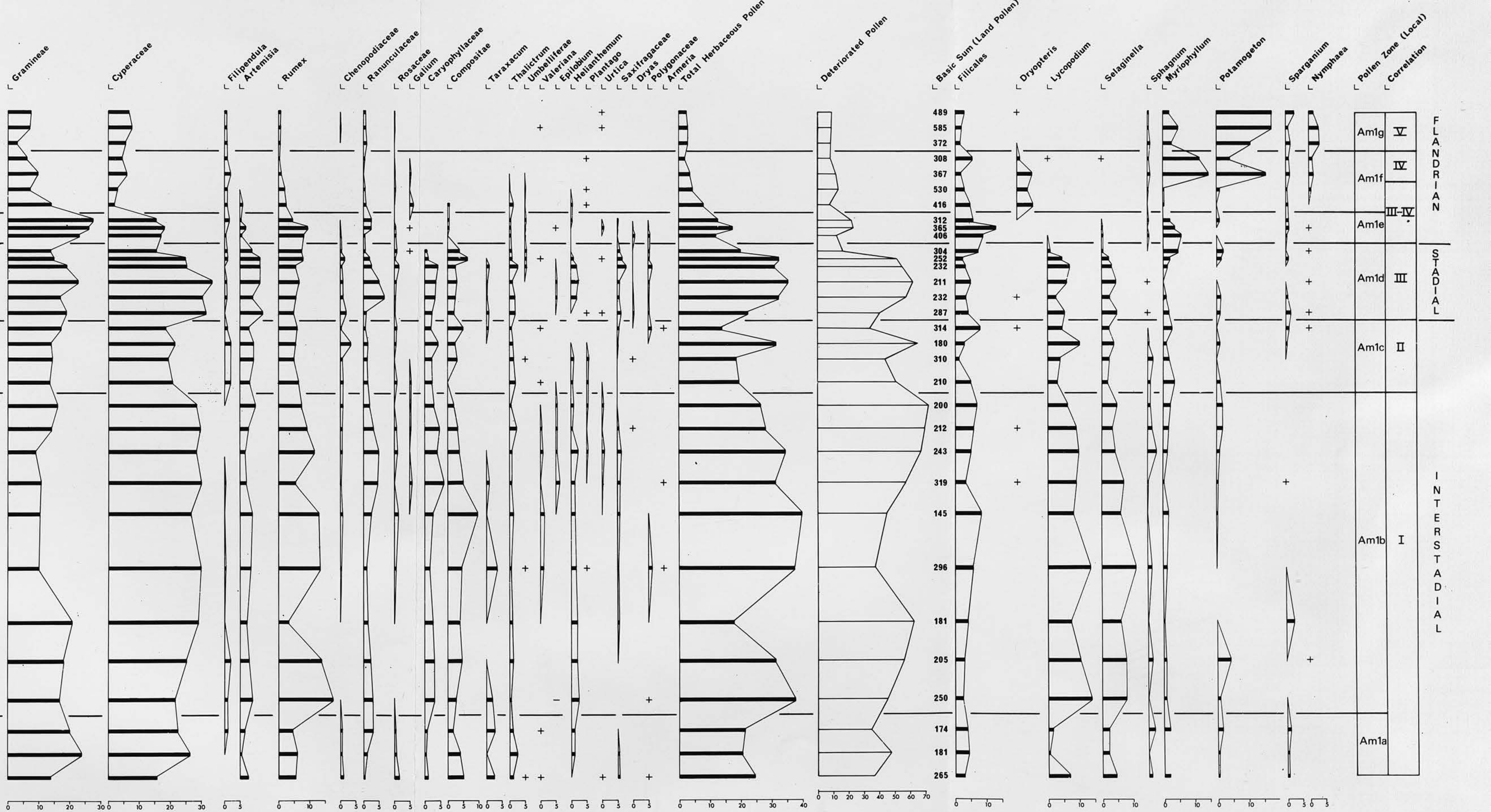


FIGURE 20 AMULREE 1: Lateglacial-early Flandrian pollen diagram. 'Total Herbaceous Pollen' excludes Gramineae and Cyperaceae.



Gramineae
Cyperaceae
Filipendula
Artemisia
Rumex
Chenopodiaceae
Ranunculaceae
Rosaceae
Galium
Caryophyllaceae
Compositae
Taraxacum
Thalictrum
Umbelliferae
Valeriana
Epilobium
Helianthemum
Plantago
Urtica
Saxifragaceae
Dryas
Polygonaceae
Armeria
Total Herbaceous Pollen
Deteriorated Pollen
Basic Sum (Land Pollen)
Filicales
Dryopteris
Lycopodium
Selaginella
Sphagnum
Myriophyllum
Potamogeton
Sparganium
Nymphaea
Pollen Zone (Local)
Correlation
489
585
372
308
367
530
416
312
365
406
304
252
232
211
232
287
314
180
310
210
200
212
243
319
145
296
181
205
250
174
181
265
Am1g
Am1f
Am1e
Am1d
Am1c
Am1b
Am1a
V
IV
III-IV
III
II
I
FLANDRIAN
STADIAL
INTERSTADIAL

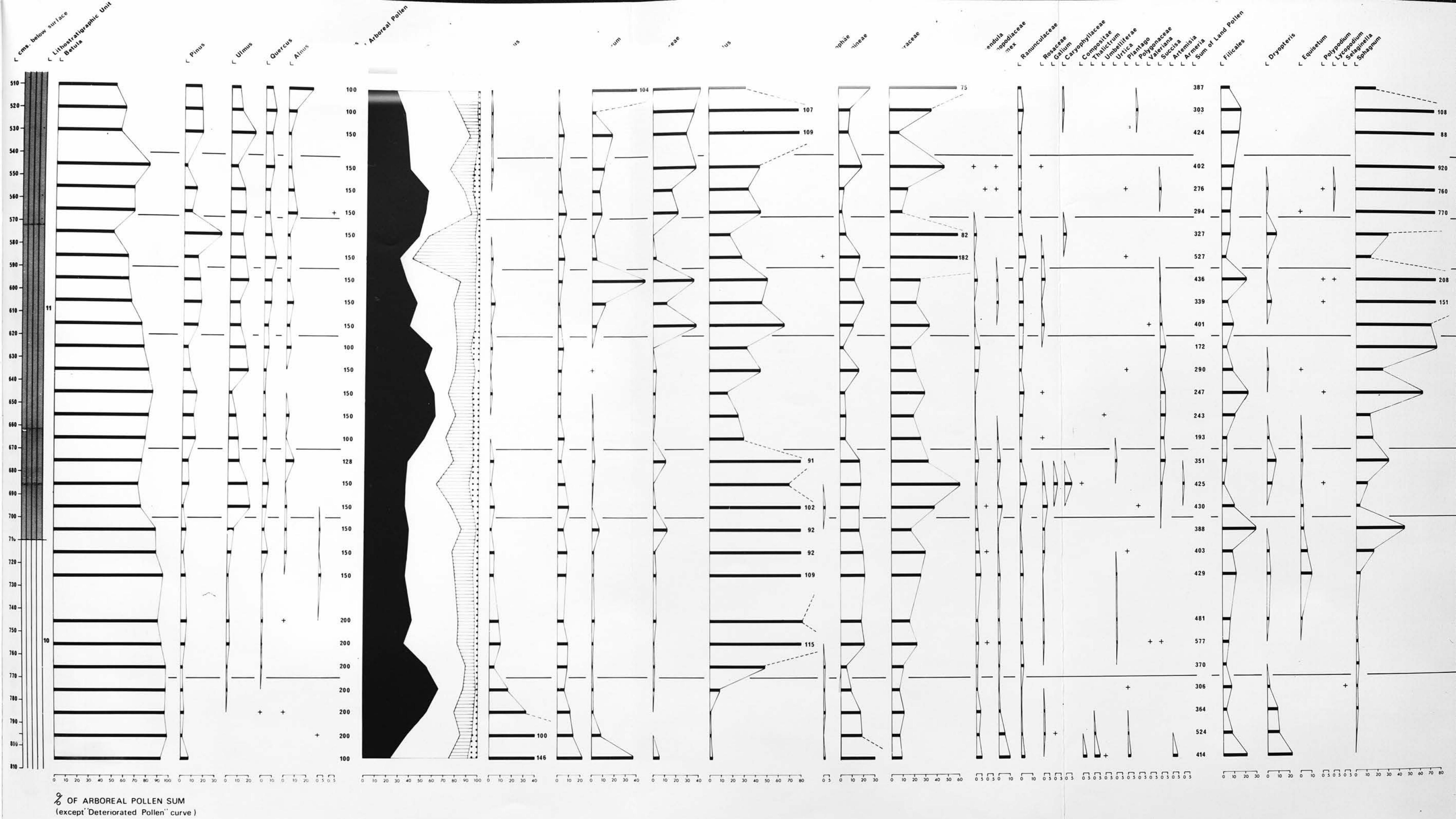
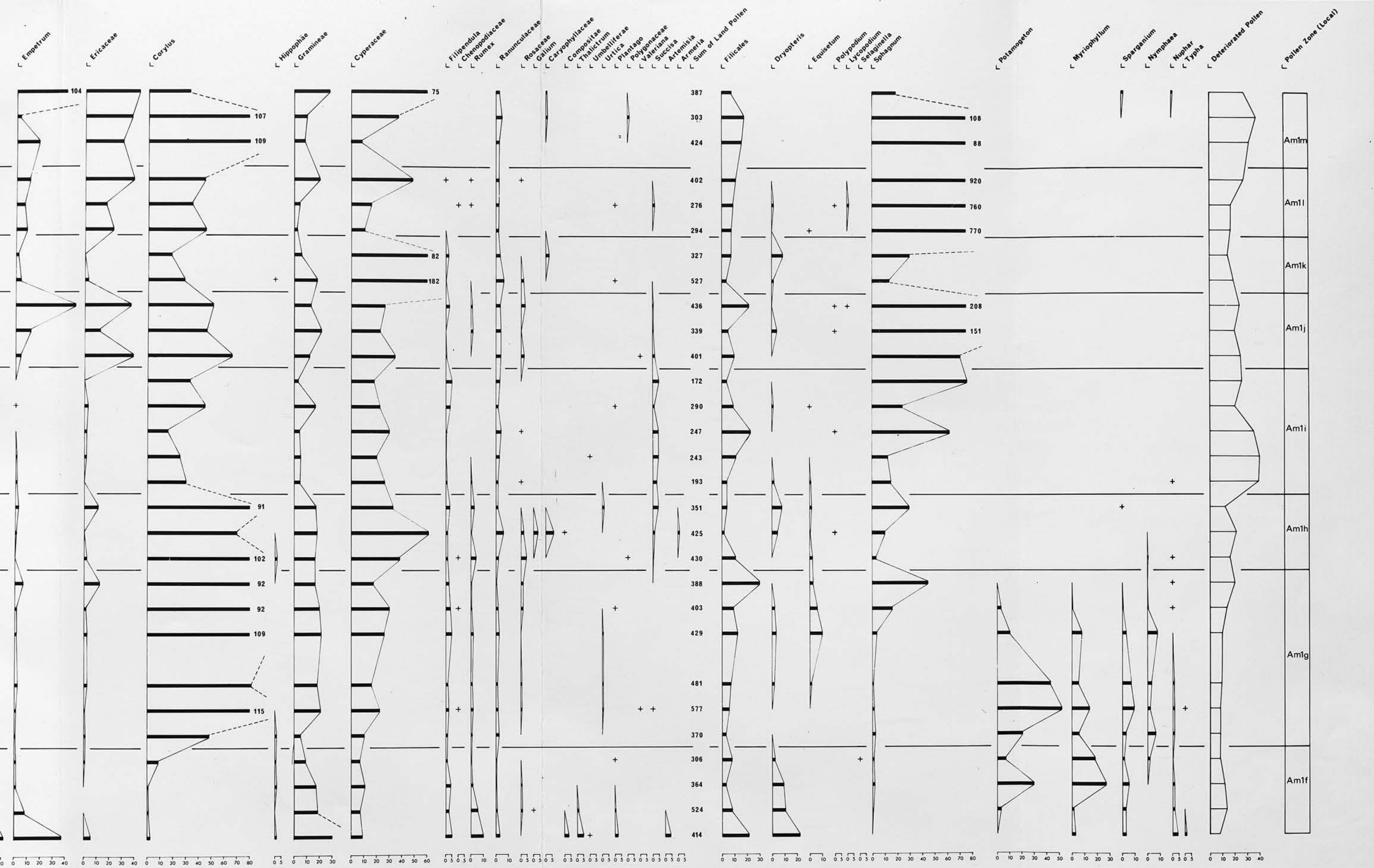


FIGURE 21 AMULREE 1: pollen diagram through lower Flandrian sediments.



Empetrum
Ericaceae
Corylus
Hippophäe
Gramineae
Cyperaceae
Filipendula
Chenopodiaceae
Rumex
Ranunculaceae
Rosaceae
Galium
Caryophyllaceae
Compositae
Thalictrum
Umbelliferae
Urtica
Plantago
Polygonaceae
Valeriana
Succisa
Artemisia
Armeria
Sum of Land Pollen
Filicales
Dryopteris
Equisetum
Polypodium
Lycopodium
Selaginella
Sphagnum
Potamogeton
Myriophyllum
Sparganium
Nymphaea
Nuphar
Typha
Deteriorated Pollen
Pollen Zone (Local)
Am1m
Am1l
Am1k
Am1j
Am1i
Am1h
Am1g
Am1f
387
303
424
402
276
294
327
527
436
339
401
172
290
247
243
193
351
425
430
388
403
429
481
577
370
306
364
524
414

FIGURE 22 AMULREE 2: Lateglacial-early Flandrian pollen diagram and radiocarbon dates. 'Sum of Herbaceous Pollen' excludes Gramineae and Cyperaceae.

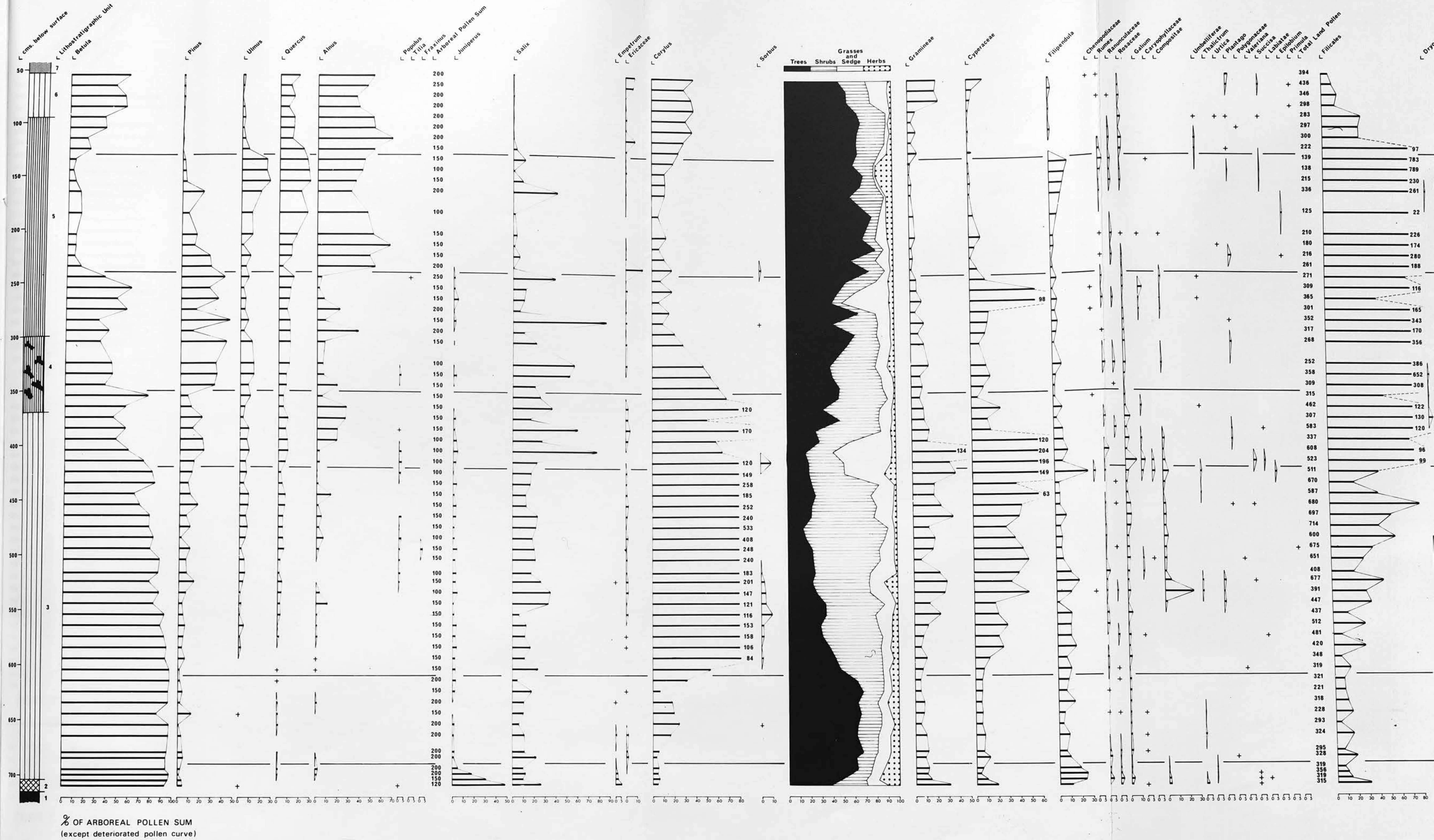


FIGURE 24 MOLLANDS: Flandrian pollen diagram.


Empetrum
Ericaceae
Corylus
Sorbus
Trees
Shrubs
Grasses and Sedge
Herbs
Gramineae
Cyperaceae
Filipendula
Chenopodiaceae
Rumex
Ranunculaceae
Rosaceae
Galium
Caryophyllaceae
Compositae
Umbelliferae
Thalictrum
Urtica
Plantago
Polygonaceae
Valeriana
Succisa
Labiatae
Epilobium
Primula
Total Land Pollen
Filicales
Dryopteris
Equisetum
Polypodium
Lycopodium
Selaginella
Sphagnum
Potamogeton
Myriophyllum
Sparganium
Nymphaea
Nuphar
Typha
Sum of Deteriorated Pollen
Pollen Zone (Local)
Mo h
Mo g
Mo f
Mo e
Mo d
Mo c
Mo b

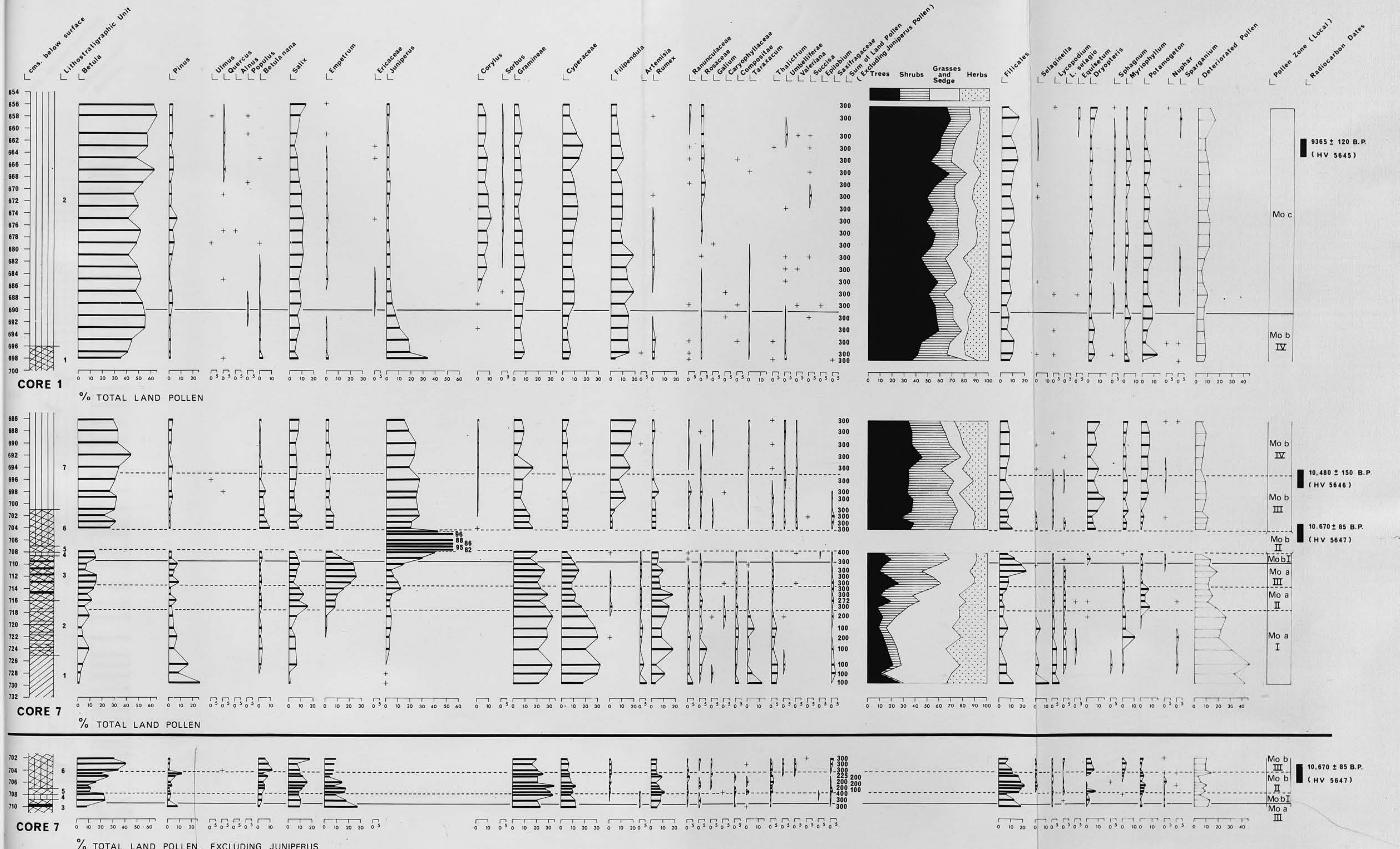


FIGURE 25 MOLLANDS: pollen diagrams through basal sediments, and radiocarbon dates.

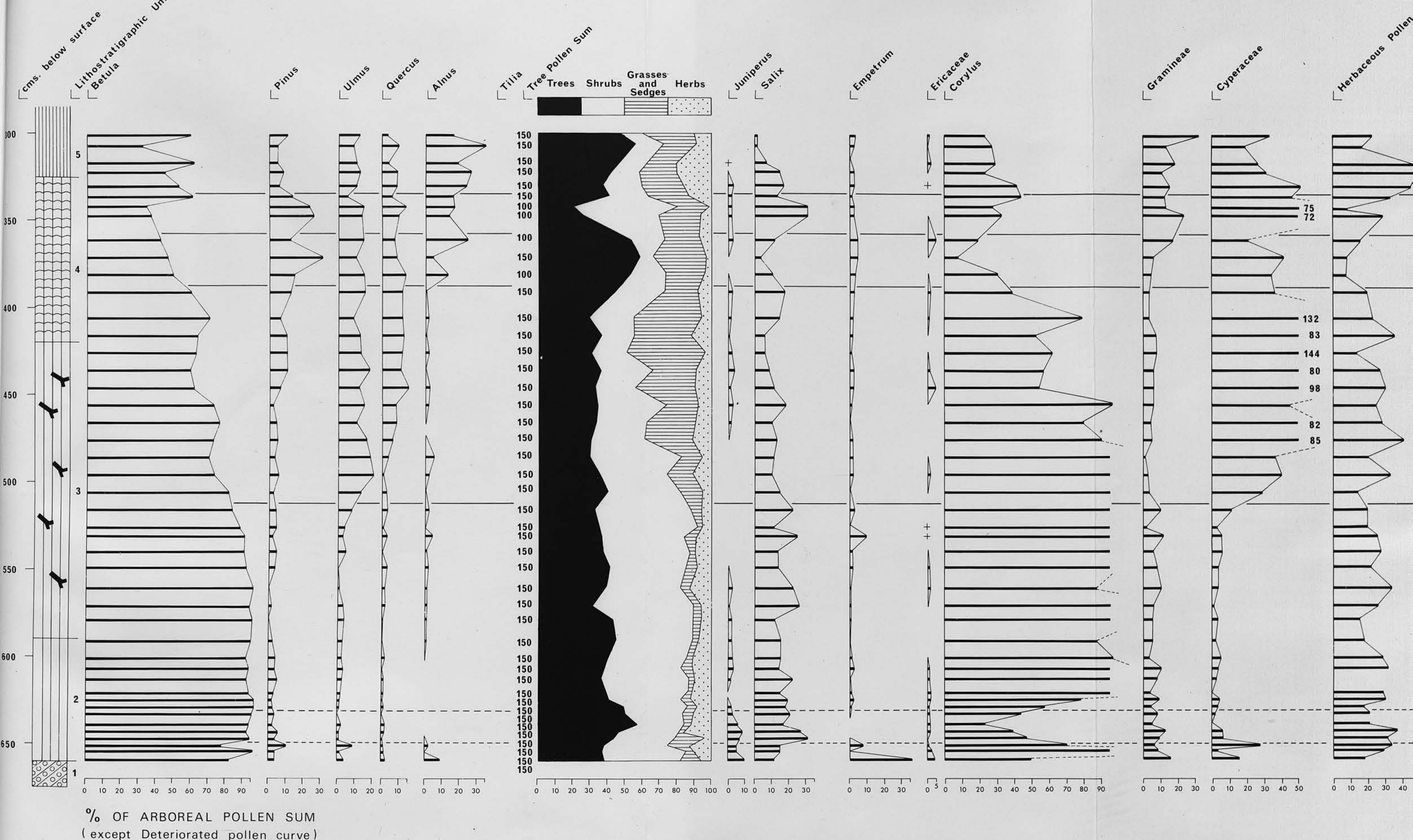
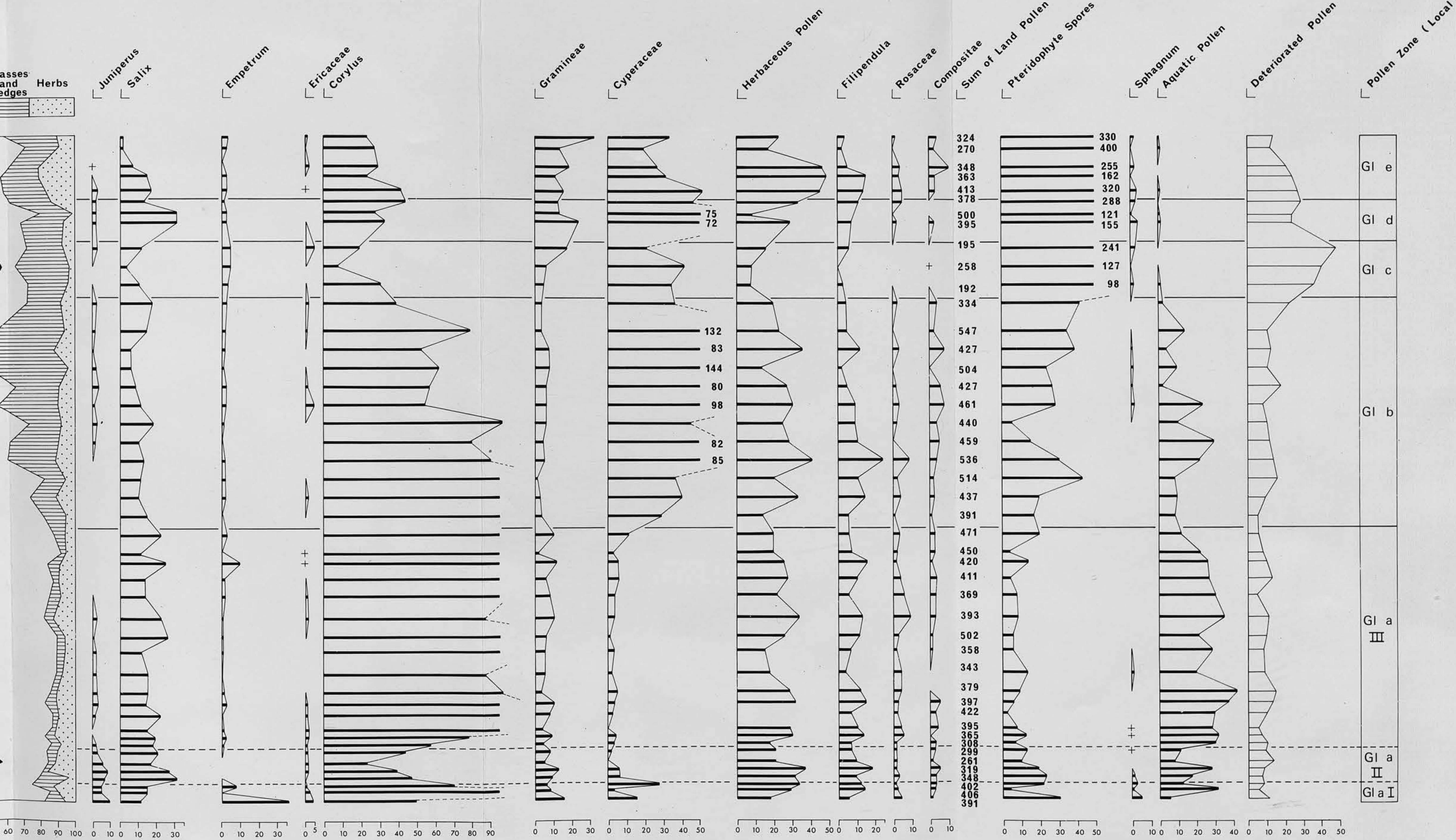


FIGURE 26 GLENTURRET: pollen diagram through basal sediments.
'Herbaceous Pollen' excludes Gramineae and Cyperaceae.



Grasses and Sedges
Herbs
Juniperus
Salix
Empetrum
Ericaceae
Corylus
Gramineae
Cyperaceae
Herbaceous Pollen
Filipendula
Rosaceae
Compositae
Sum of Land Pollen
Pteridophyte Spores
Sphagnum
Aquatic Pollen
Deteriorated Pollen
Pollen Zone (Local)
Gl e
Gl d
Gl c
Gl b
Gl a III
Gl a II
Gl a I